

**UNDERGRADUATE STUDENTS' UNDERSTANDING OF
CONCEPTS FOUNDATIONAL TO THE LEARNING OF QUANTUM
MECHANICS (QM) VIA MODELS-BASED INQUIRY**

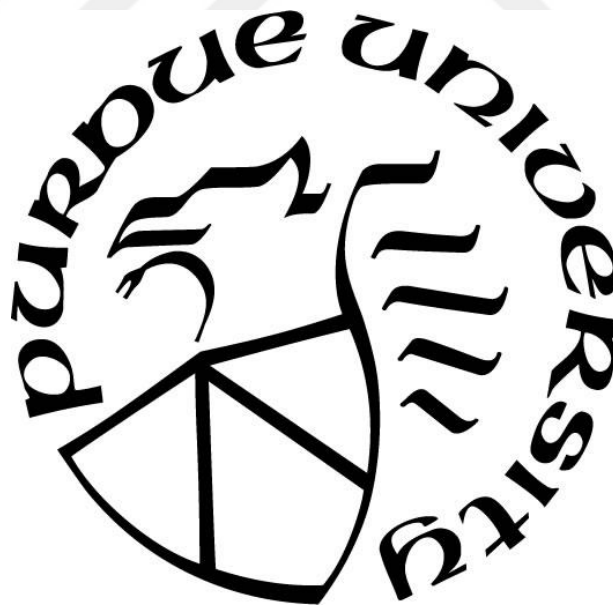
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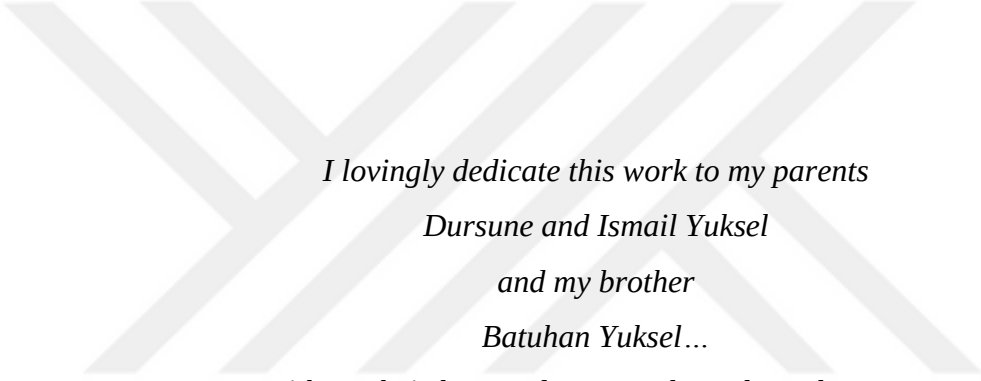
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*I lovingly dedicate this work to my parents
Dursune and Ismail Yuksel
and my brother
Batuhan Yuksel...*

*Without their love and support throughout the years,
I would not be the person I am today.*

*Bu calismami sevgilerini ve desteklerini hayatimin
her alaninda, ozellikle de doktora surecinde
benden esirgemeyen sevgili aileme ithaf ediyorum...*

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ABSTRACT

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Title: Undergraduate Students' Understanding of Concepts Foundational to the Learning of Quantum Mechanics (QM) via Models-Based Inquiry.

Major Professor: Dr. Lynn A. Bryan

Studies on secondary and undergraduate students' quantum mechanics (QM) understanding are quite limited in comparison to studies examining students' understandings of classical mechanics. Developments in science and technology, particularly at the nanoscale, have brought attention to the importance of learning quantum physics and its applications not only at the undergraduate level, but also as early as high school. Many postsecondary physics and engineering programs require students to take QM courses. Therefore, the need for research in QM learning has become indispensable, particularly with students' common negative perceptions of QM and their low-level of achievement in these courses (Singh et al., 2006). In this study, I examined undergraduate freshmen and sophomore college-level students' understandings and reasoning of fundamental quantum mechanics concepts as they engaged in a model-based learning module (MBLM). Informed by a pilot study in which I examined engineering and physics students' understanding about basic quantum phenomena (i.e., structure of an atom, energy levels, and atomic spectroscopy), I developed a MBLM for the current investigation. In this study, participants were assigned to one of two groups: intervention and control. The intervention group received a MBLM that guided students to use their reasoning by utilizing physical and visual models with the help of computer-based simulations as well as hands-on models. The control group, on the other hand, received

the traditional instructional unit that included textbook and computer-based simulations. Students in both groups engaged with assigned learning materials throughout four weeks (eight hours in total), and after every one or two lessons they took inter-lesson assignments. In order to track growth in students' reasoning and understanding, drawings, diagrams, written and oral explanations, discussions and interviews were collected for both quantitative and qualitative analysis. Based on students' responses in pre- and post-questionnaires, worksheet and inter-lesson assignments, I developed a rubric that includes four model levels: Discrete entity (particle), hybrid, quantum-like and quantum models. As a result, the MBLM group performed better on shifting their model toward targeted (quantum-like or quantum) models than TCBS group. A quantitative analysis showed that model-based inquiry activities facilitated students who were initially in the discrete entity (particle) and hybrid model levels to shifting toward quantum-like and quantum model levels in comparison to traditional textbook and computer-based simulation activities. Moreover, the analysis showed that MBLM students constructed meaningful conceptual understanding and scientifically accurate terminology. Implication for physics courses and teaching/ learning physics are also discussed.

1. INTRODUCTION

Researchers in physics education have primarily focused on students' understanding of classical mechanics such as force, velocity, motion, work and energy, as well as electricity and magnetism (Mashhadi & Woolnough, 1999; Pfundt & Duit, 2000). In contrast, studies focusing on quantum mechanics are quite few and limited, since these concepts are considered as primarily expert oriented (Fischler & Lichtfeldt, 1992; Johnston, Crawford, & Fletcher, 1998; Whittmann, Steinberg, & Redish, 2002). The potential impact of the rapid developments in science and technology, particularly at the nanoscale, have brought attention to the importance of learning quantum physics and its applications not only at the undergraduate level, but also as early as high school. Many post-secondary physics and engineering programs require students to take quantum mechanics courses, however, the rate of students' success in these courses does not seem promising (Akarsu, 2010; Akarsu, Coskun, & Kariper, 2011; Sadaghiani & Bao, 2006; Singh, 2001 2008; Witthmann et al., 2002).

Researchers have suggested that the underlying reasons for student difficulties in learning quantum mechanics is because the concepts are largely ontological in nature (Mannila, Koponen, & Niskanen, 2002), contain advanced mathematical components (Pospiech, 1999), and present a conflict between classical and quantum points of view (Fischler & Lichtfeldt, 1992; Johnston et al., 1998). Therefore, the need for understanding how students come to understand quantum mechanics concepts and how the field of physics education can support their learning has become indispensable, particularly with students' common negative perceptions of quantum mechanics and their low-level achievement in these courses.

1.1 From Deterministic to Probabilistic

The nature of quantum mechanics concepts presents learning and teaching difficulties at all levels, from secondary to post-secondary education. One of the principal sources of confusion that students encounter occurs when they attempt to explain quantum behavior of sub-atomic particles with Newtonian physics (Fischler & Lichtfeldt, 1992; Johnston et al., 1998; Mannila, Koponen, & Niskanen, 2002). Newtonian mechanics relates to macroscopic objects' motion and dynamics. In the Newtonian world, objects generally behave similarly, and their behaviors can be predicted with known variables; however, quantum mechanics approaches phenomena from a probabilistic perspective. There is no absolute truth or prediction for the behavior of individual microscopic particles.

With our current understanding of science, it is cognizable that everything around us is part of a quantized system. Even objects or phenomena that we believe have a continuous structure are made out of quantized pieces (Taber, 2004). Unlike continuous systems, quantized structures have a different inner working mechanism and consequently different properties. This means that the particles of an object at the quantum scale may have a completely different melting point, electrical conductivity, chemical reactivity, and fluorescence than the object itself has at a visible (macroscopic) scale (Gupta, 2014; Khraiche, Silva, Cauwenberghs, Lo, Wang, & Freeman, 2011).

Because of the nature of the quantum world, it is not possible to understand quantum phenomena from a classical mechanics point of view; one is required to reframe her/his thinking from deterministic to probabilistic. For example, in the early stages of the development of atomic theory, matter and its interactions were described with

existing theories, which were derived based on experimentation and observation of macroscopic world. When it became obvious that an atom and the behavior of an electron could not be explained with these theories and quantized energy levels were discovered, scientists began to reevaluate their perspective. Most scientists such as Max Born, Niels Bohr and even Albert Einstein initially did not want to accept an indeterminant view (e.g. quantum perspective) (Akarsu et al., 2011; Beller, 1990). With Max Born's probabilistic interpretation of the wave function and subsequent discoveries/theories, scientists had to admit that it was the closure of one era for physics and the opening of a new one (Beller, 1990). Today we appreciate early scientists' efforts in understanding the quantum world and discoveries that opened doors for today's scientists and engineers since many technological advances in science have emerged based on their discovery of different properties of sub-atomic (micro- and nano-level) particles.

1.2 Historical Foundations of Atomic Model

The history of quantum theory started with scientists accepting the failure to explain the behavior of subatomic level particles from their ontological perspective of science. Scientists tried to find answers for some crucial questions such as what is the nature of matter and what is the origin of the universe. Moreover, many scientists developed a theory upon their experiments and observations that attempted to clarify the mystery behind phenomena that were observed. Most of the time, the results of experiments that were perceived and interpreted by scientists culminated in a theory until another scientist conducted a new experiment and propounded a new theory that was built upon a previous one or that was completely different if the new understanding was radically different from the new theory's predecessor (Kuhn, 1970).

The discovery of atomic structure and quantum theory epitomizes *ad hoc* changes or paradigm shifts (Kuhn, 1963). When J. J. Thomson was interested in the nature of electricity with Maxwell's electrodynamics in mind, many scientists had already conducted experiments with cathode tubes and published their results to shed light on the discussion of whether cathode rays were either particle or waves in the ether (Niaz, 1998). Even though Thomson did not have a clear idea about the nature of rays at that time, after iterative experiments he concluded that cathode rays were negatively charged and carried by particles of matter (Thomson, 1897). Moreover, in the same article, Thomson stated his theory about atoms of different elements as "the atoms of the different chemical elements are different aggregations of atoms of the same kind" (Thomson, 1897, p. 311). Based on his findings from the cathode tube experiment, his hypothesis turned into a theory for an atomic model that seemed to be widely accepted by scientists who tended to believe particle theory (Niaz, 1998).

Rutherford and his colleagues, on the other hand, were focusing on radioactivity by sending alpha particles to gold foils. Since the Thomson atom model stated that negatively charged particles were scattered in the positively charged area of the atom, they expected that alpha particles would mostly pass through the gold foil, however, they encountered an unexpected observation of scattering alpha particles with a large angle. For a long time (from June 1909 to May 1911), Rutherford and his colleagues tried to explain anomalies that emerged in their experiment by the established models, however, after many efforts, they had to devise a new model that seemed to work explaining current anomalies (Niaz, 1998). This new model was also widely accepted by physicists and the chemists who thought that it was explanatory for many problems in those fields

(Wilson, 1983). By that time, a new researcher, Niels Bohr, started working on Rutherford's atom with Rutherford himself (Ford, 2009). Max Planck and Albert Einstein had already made substantial progress on introducing quantization of light (Zeilinger, 2000). Bohr submitted to Rutherford a draft of his innovative ideas on quantized energy levels, which were the two unexplained phenomena in the Rutherford model of the atom, the hydrogen atom spectra and the paradoxical stability of electron (Ford, 2009; Lakatos, 1970; Niaz, 1998). Although Bohr and Rutherford were conscious of the limitations this theory had for explaining only the hydrogen spectrum and not multiple atoms' spectra, they published Bohr's theory in 1913. In their publication, Heilbron and Kuhn (1969) drew attention to Bohr's theory which consisted of both classical and quantum theory: "...Bohr had developed a detailed, non-spectroscopic, quantized version of Rutherford's atom some time before he saw the relevance of the Balmer formula" (p. 255).

Furthermore, Holton (1986) said:

"While in the stationary states, the atom obeys classical laws of mechanics, those going back to Newton; while the atom emits such radiation, however, it chiefly exhibits quantum behavior, by laws first proposed by Planck in 1900. Thus, Bohr's atom of 1913 was really a kind of mermaid - the improbable grafting together of disparate parts, rather than a new creation incorporating quantum theory at its core" (p.145).

That being said, the Bohr model still seemed to be a groundbreaking theory when it was first published. However, his article had not been well received by many physicists. In fact, famous physicists such as Otto Stern, Lord Rayleigh, H. A. Lorentz, Ehrenfest and J. J. Thomson explicitly expressed their dissatisfaction with Bohr's theory (Holton, 1986; Niaz, 1998; Pais, 1991). It was a matter of time before physicists realized that quantum theory opened a door to a new era which that led to many improvements in science and technology. Between 1920 and 1930, atomic structure had become more

understandable with the development of the mathematical formulations of quantum mechanics by Werner Heisenberg and Erwin Schrödinger (Zeilinger, 2000). They went down in the history of quantum mechanics with their theoretical works in which each explained the same quantum model of an atom from a different perspective.

At the beginning of the twentieth century, scientists changed their point of view on sub-atomic phenomena, which led to a fundamental paradigm shift (Kuhn, 1970). With the new paradigm, phenomena in the micro/nano world could be explained and interpreted, and yet it opened a new era for technological and scientific improvement.

1.3 Challenges in Quantum Mechanics Understanding

With the predominant utilization of quantum mechanics and nanoscale science, societies have come to realize the tremendous need for people to be educated in these areas of science. Correspondingly, efforts for understanding and learning quantum mechanics and nanoscale science for undergraduate engineering and physics students have also increased. Research on quantum mechanics education has concentrated on answering two major questions: 1) Why is learning quantum concepts very challenging, and 2) What can be done to help students succeed in acquiring important quantum concepts? (Mannila, Koponen, & Niskanen, 2002).

It is an intuitive notion that student's understanding of science is directly related to their attitudes toward science (Furlan, 2009; Pintrich, 1999). Students who think science topics are interesting, related to their personal experiences, and useful for understanding the world around them tend to devote more effort and time to their science learning (Furlan, 2009). Unfortunately, many students do not believe that quantum mechanics corresponds to their present-day needs (Kalkanis et al., 2003). Instead,

students find classical physics more relevant to many aspects of their life and can utilize their physics knowledge in their daily life to solve problems. As a result, macro world jargon has become integrated into daily life, consciously and subconsciously (e.g., “work”, “force”, “energy”). Unlike classical mechanics, quantum mechanics concepts consist of technical terms that an individual would not typically use or directly see in every day experiences (Bethge & Niedderer, 1996). Although possessing rich or poor vocabulary is not a predictor of students’ level of understanding in communicating science (Lee, Fradd & Sutman 1995), confusing daily use of some science terminology with technical terminology could create learning difficulties (Hodson, 1993). Hence, it is important to put forth extra effort to make oneself familiarized with quantum terminology as well as their applications.

Another obstacle of understanding quantum mechanics comes from its nature. The quantum world has different and relatively extraordinary rules in comparison to the classical world. As a widely-used teaching strategy in quantum mechanics courses, traditional instruction seems to be reinforcing the notion that students to combine and blend concepts of classic mechanics and quantum mechanics (Kalkanis et al., 2003). Mannila, Koponen, & Niskanen (2002) categorized students’ conceptions on quantum mechanics in four particular models: 1) quasi-classical (particle ontology based), 2) trajectory based, 3) statistical (probabilistic) and 4) quasi-quantum. While quasi-classical and trajectory based categories are most dominantly used by students when they solve a quantum mechanics problem, considerably fewer numbers of students mix probabilistic and quasi-quantum models in their reasoning (Mannila, Koponen, & Niskanen, 2002). The mixed models are mainly reinforced by school curricula that is developed based on a

hybrid model (Justi & Gilbert, 2000) or by misleading textbooks which are poorly written (Shiland, 1995; Tsapalis, 1997). In order for students to distinguish both quantum phenomena and terminology from classical mechanics, the difference needs to be emphasized in the curriculum in order to facilitate them in constructing their understanding in a more logical and organized and meaningful way. As Jonassen, Howland Moore and Marra (2004) states, students learn in a meaningful way if they engage with a more active learning environment and construct their internal models intentionally. When meaningful learning occurs, individuals construct sturdier and more comprehensive internal models. Consequently, they can understand more complex ideas such as quantum mechanics. I propose that model-based learning which was branched from constructivist learning theory and more specifically inquiry-based learning will facilitate students overcoming their conceptual challenges and guide them through constructing meaningful understanding.

1.4 Purpose of the Study

With the specific objective of developing the conceptual understanding of quantum mechanics of undergraduate university level students, this study is grounded in the theory of model-based learning. This study contributes to our understanding of students' initial models of atomic structure, energy levels, and atomic spectra. Students' responses indicated how they understood and constructed their models based on the orientation to instruction (i.e., model-based instruction versus traditional instruction). This study also allowed for a comparison of students' models across different contexts and investigated the reason behind students' alternative models.

Furthermore, this study helped us to understand the model evolution phases while

students took charge of their model construction via model-based instruction. Empirical research on individuals' cognitive thinking and knowledge construction indicates that internal models are built as a systematic representation of the real world as a result of the process of perception and subjective conceptualization (Johnson-Laird, 1983).

Constructivist epistemology, furthermore, argues that we know external reality within the limit of our own experiences and define reality according to our own perspective (von Glaserfeld, 2001, Riegler, 2001). In other words, external reality is not mind-independent; everything we observe, describe, and make sense of in nature is nothing but a representation of our experience (von Glasersfeld, 1995). Thus, each student's model development stages may show variety even though they engaged with the same models and support materials. This study analyzed different models propounded by students as well as the reasoning that reflects why they developed the model and particular conceptual understanding. The results of this study have implications for science education researchers and curriculum developers regarding students' learning of fundamental quantum concepts.

1.4.1 Research Questions

This study examined undergraduate students' development of understanding concepts related to three fundamental quantum mechanics topics (structure of the atom, energy levels, and atomic spectra) as they learn through engaging in modeling-based inquiry instruction designed to scaffold their construction of knowledge. The research questions guiding this study were:

1. What are students' pre-intervention understandings about the structure of the atom, energy levels, and atomic spectra?

2. How do students represent their understanding (i.e. what are their developing models) of the structure of the atom, energy levels and atomic spectra as they learn about these topics?
3. How do students' understanding about the structure of the atom, energy levels, and atomic spectra as a result of their participation in a modeling-based learning module (MBLM) that is designed to scaffold their development of understandings (i.e. the intervention group) compare to students' understanding about the structure of the atom, energy levels, and atomic spectra as a result of their participation in a traditional, textbook-based instruction (the control group)?

1.5 Significance of the Study

Although many studies focus on common misconceptions that students have about the structure of the atom, energy levels, and atomic spectra, few studies propose an innovative approach to facilitate students in overcoming their learning challenges and addressing their misconceptions. In this study, I aim to provide a model-based learning environment that helps students construct knowledge in a meaningful order and evaluate, revise, and refine existing models (Buckley, 2000; Clement, 1989; Gobert & Buckley, 2000). These results suggest that traditional textbooks and computer simulations help students learn basic quantum mechanics concepts but leave them with an ambiguous understanding. On the other hand, a learning environment supported with model-based activities encourages learners to question their existing models, examine (if the model represents real phenomena) and, if necessary, to alter their model toward the target model. It also encourages individuals to develop terminology, retaining it for further use.

This study will be of interest to science researchers who focus their attention on how students can acquire complex knowledge such as quantum mechanics by utilizing different types of models. Some researchers have examined college students' conceptual knowledge about higher-level quantum topics to reveal their challenges, misconceptions, or alternative concepts; however, most of them were limited to suggesting innovative instructional strategies that facilitate the students' learning process. Since quantum mechanics concepts are very abstract and non-observable at the macro level, traditional instruction, books, and even computer simulations do not offer students any conceptual understanding other than reinforcing their non-scientific models. Therefore, this study aims to take a pioneering role in offering an innovative strategy by utilizing model-based inquiry to improve conceptual understanding and model-based reasoning to make connection between concepts. Those who are interested in research with regard to obstacles in science and model-based learning will benefit from this study.

2. CONCEPTUAL FRAMEWORK AND REVIEW OF THE LITERATURE

The framework used to establish this study was drawn from three bodies of theories and research: i) Constructivism as learning theory, ii) Modeling and model-based reasoning as theoretical framework, and iii) Quantum mechanics learning and conceptual challenges as science/ physics content. In this chapter, I delineate my perspective of constructivism and model-based reasoning theories as well as review of current literature in research on model-based learning / inquiry which are examples of the instructional design to promote model-based reasoning. Will also discuss about the review of current literature in models used in quantum mechanics learning and general quantum mechanics research. By doing that, I compose my rationale for using this theory as conceptual framework to the current study.

2.1 Constructivism: Implications for Learning Environment

Throughout the past few decades, how individuals learn has been the focus of research questions by educational scientists in various fields (Bransford et al., 2000; Novak & Gowin, 1984; Piaget, 1976). Educational psychologists have examined individuals' learning processes from different perspectives propounded by learning theorists. Scholars have used variations of three major philosophical frameworks as the foundation for studying learning: behaviorism, cognitivism and constructivism.

Behaviorist theory focuses on the observable outputs of learning (Good & Brophy, 1990). This theory originated back to Aristotle's idea of association between existence and events (Mergel, 1998). Later, other scientists including Pavlov (1949-

1936), Thorndike (1874-1949), Watson (1878-1958) and Skinner (1904-1990) followed Aristotle's footsteps and developed behaviorist theory based on experiments or observations of human behavior (Mergel, 1998). The common theme from these experiments or observational outcomes was that in order to learn about the outside world, individuals' behavior should be trained accordingly (Skinner, 1971). They also claimed that internal processes and knowledge construction are not important either in the learning process or in understanding human behavior (Bargh & Ferguson, 2000). From a behaviorist perspective, learners are considered passive actors who need specific directions, additional support and motivation (Skinner, 1953). Moreover, learners are expected to make good observations, listen to instructions very carefully and engage with activities (or any other kinds of learning practice) in order to learn (Fosnot, 1996). Since behaviorist theory ignored the fact that internal processing along with experiences are a big predictor for human behavior and understanding, that theory was condemned to be failure. When scientists in epistemology closely examined human behavior and tried to answer the question of how individuals make sense of the world, they came up with an argument that information is processed by individuals piece by piece in an individual's mind (Piaget, 1952). In Piaget's work with children's knowledge acquisition, he mentioned the developmental stages called assimilation, equilibration, disequilibrium, and accommodation (see Figure 2.1).

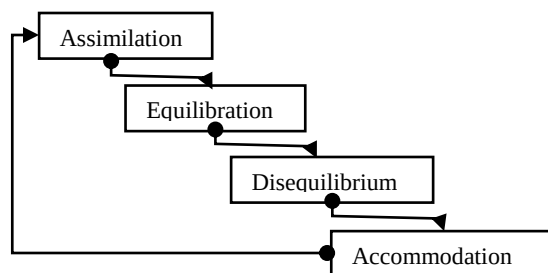


Figure 2.1: Piaget (1952)'s process of adaptation

Based on these developmental stages, he proposed that knowledge acquisition happens by virtue of an individual's experience with the external world leading to the construction of knowledge in an organized way (Bodner, 1986). First, an individual tries to assimilate new information by structuring the knowledge based on his/her existing models/schemas. Second, the individual wants to fit this new information into existing models. By doing that s/he tries to keep equilibrium between new and old knowledge. Disequilibrium occurs when s/he cannot fit the new piece of knowledge into her/his existing model. Accommodation, on the other hand, involves adjusting the existing model to the new situation in order to make sense of the reality.

Lev Vygotsky, who is another psychologist/ constructivist, proposed that learning occurs as a result of the social interactions of learners. His theory of sociocultural constructivism argues that individuals are part of their cultural environment and their cognitive process cannot be understood if they are evaluated independently from their social settings (Woolfolk, 2004). Different from Piagetian constructivism, sociocultural constructivist theory argues learning is assisted by others (Tudge & Winterhoff, 1993). Consequently, collaboration between peers plays a significant role in children's intellectual growth. Additionally, according to Vygotsky, "cultural tools" are very important for cognitive processing. In order to share ideas, individuals use language, any

kind of cultural symbols, media, etc. (Woolfolk, 2004). Similar to Piaget, Vygotsky claims children's intellect is correlated with their age and thus their mental development (Vygotsky, 1978a, 1978b); however divergently from Piaget's theory, Vygotsky believed that children's mental capability can be improved by giving proper aid from external sources. He called this approach as zone approximate development (Vygotsky, 1978b).

Von Glaserfeld, who is another constructivist theorist, claimed that understanding the external reality is within the limit of individuals' experiences and the reality is defined according to individuals' own perspective (Glaserfeld, 1995, 2001; Riegler, 2001). In other words, the external reality is not mind-independent. That means, everything we observe, describe and make sense in nature is nothing but a representation of our experience (von Glasersfeld, 1995). Based on this idea, many constructivists argue that individuals' subjectively constructed models play a significant role in building a meaningful understanding and constructing new scientific models.

Cognitive theory argues that learning occurs as a result of information processing. According to cognitive theory, developing models and utilizing them to understand the world are regular processes in every individual's mind (Gentner, 2002; Johnson-Laird, 1983). People naturally observe and make connections between related phenomena and create models, which they use to make sense of external reality. In other words, models are tools for individuals to internalize knowledge and store in a logical way based on their experiences (Ravanis, Pantidos, & Vitoratos, 2010) and existing models (Cepni & Keles, 2006; Piaget, 1976; Pirnay-Dummer, et al., 2012). New knowledge may or may not accord with the individual's existing model depending on the representation that has been used by the individual (Pirnay-Dummer, et al., 2012). In those cases, developing a

new model compatible with the new situation becomes necessary. Therefore, each model is constructed as an idiosyncratic and symbolic representation of phenomena in the external world (Markovits, 2012; Pirnay-Dummer, et al., 2012). Individuals tend to develop practical models rather than using deductive reasoning to evaluate, review, and revise the other possible models (Johnson-Laird, 1983). With that information in mind, the primary question investigated by cognitive scientists is how the modeling or reasoning process occurs in an individual's mind. Cognitive researchers asserted that using analogies facilitated the model constructing process (Collins & Gentner, 1987). Recent studies also indicated that using dynamic models allows individuals to manipulate their own models (Clement, 2003; Craig, Nersessian & Catrambone, 2002). Analogies and dynamic models are vehicles which accompany an individual's reasoning during conceptual change and model alteration. Therefore, model-based learning theory has been recognized as one of the most innovative strategies in science education (Buckley, 2000; Clement, 1993a, 1993b, 1993c, 2000; Clement & Ramirez, 2008; Hansen et al., 2004; Harrison & Treagust, 1996; Louca & Zacharia, 2012; Maia & Justi, 2009; Nersessian, 1999, 2009).

2.2 Theoretical Framework: Model-Based Reasoning

Models are representations or simplified versions of a concept, an object, or a phenomenon (Gilbert & Boulter, 2000). Models are utilized to make demonstrations, predictions, and examinations of those objects or phenomena (Passmore et al., 2009). Models have been used to embody a theoretical phenomenon into something that can be investigated, communicated, and explained as the working mechanism of that phenomenon (Passmore et al., 2009). Some cognitive scientists who has been studying

how individuals make sense of things around them advocate the idea that people learn and understand better when they construct their reasoning and along with that their representations of the phenomena in an organized way. Philip Johnson-Laird who is one of the leading cognitive scientists asserted “... *human beings understand the world by constructing working models of it in their minds. Since these models are incomplete, they are simpler than the entities they represent.*” (Johnson-Laird, 1995, p.10). His assertion indicates that individuals need to have operational and working models to make sense of the real phenomena. He also emphasized that individuals’ reasoning levels are highly predictive of their understanding of physical phenomena (Jonson-Laird, 2005). Models that help conceptual understanding are an important factor in changing an individual’s perspective with regard to giving meaning to scientific phenomena since they offer meaningful explanation and opportunity for a more tangible analysis (Clement, 2000). Being exposed to different models that represent a different dimension of real objects or phenomena gives individuals the opportunity to increase the sophistication of their reasoning and representation, which helps them to internalize and externalize the scientific concept.

Nersessian and Clement along with other researchers asserted that model-based reasoning can provide a good mediator for students’ cognitive development and conceptual change in particularly science concepts. Conceptual change in science learning occurs if learners use and create accurate scientific analogies, visual or physical models (Nersessian, 1999). Model-based reasoning is quite a useful tool for many different fields (Derry, 1999; Frigg & Hartmann, 2006; Giere, 1988; Gilbert & Boulter, 2000; Passmore et al., 2009). Furthermore, model-based reasoning plays an important

role in bringing together an individual's subjective understanding with mathematical and conceptual facts of scientific theories (Lehrer, Horvath, & Schauble, 1994). By using mathematical notations, it is possible to create an imaginary chain of events or an abstract "mental universe" to model the real world phenomena (which is impossible to observe or test with current resources) (Stewart & Golubitsky, 1992). In that sense, engagement with a variety of models plays a significant role in helping students advance their model-based reasoning and make sense of scientific phenomena.

The reasoning for using models in an individual's mind is quite different from the traditionally accepted notions of reasoning, inductive and deductive (Khan, 2007; Nersessian 2002). When models are involved in the reasoning process, then creative and complex thinking, the ability to visualize and make analogies all become a part of reasoning (Khan, 2007). Nersessian (1999) considers modeling practices of scientists as an important part of their reasoning and describes model-based reasoning as "*... in certain problem solving tasks humans reason by constructing an internal model of the situations, events and processes that in dynamic cases provide the basis for simulative reasoning.*" (p.12). All the efforts to understand problem solving and cognitive processes reveal that model-based reasoning is an essential component in conjunction with foundational knowledge organization to analyze and interpret the external world (Raghavan & Glaser, 1995). It starts as early as the preschool level to solve simple problems and deals with any learning difficulties (Lehrer & Schauble, 2000). However, in science courses, teachers do not often encourage students to use their reasoning skills to interpret the data; they are expected to learn data-driven methods of inquiry (Raghavan & Glaser, 1995).

Especially when studying abstract and complicated phenomena, model-based reasoning provides learners many possibilities to exercise developing and evaluating their approaches. Furthermore, model-based reasoning is one of the most significant methods for a conceptual change. Following traditional scientific methods leads to observation and interpretation of the data. However, model-based reasoning provides an opportunity to have the physical and theoretical models of a phenomenon be utilized in direct application rather than in abstraction (Raghavan & Glaser, 1995).

Reasoning via models has proven to be an influential component for conceptual understanding (Nersessian, 1999; Lehrer & Schauble, 2000). Therefore, the ability to use models and reasoning through modeling are very important aspects to be fostered during the teaching processes. Chittleborough and Treagust (2007) suggested that individuals do not innately have modeling abilities but develop and learn this after receiving instruction and doing examples.

Nersessian (1999) identified three different practices of model-based reasoning in science: creating analogies, employing visual representations, and thought experiments. These practices can be applicable for both theoretical and experimental reasoning. Lehrer, Schauble, and Penner (1995), on the other hand, suggested four different models that facilitate the development of model-based reasoning: 1) Physical models, which are the representation of the world by individuals (e.g. the solar system, human body, etc.). It has components of actual modeled objects and an individual's intuition. 2) Representational models, which are the depiction of the actual world (such as maps, schemas, diagrams etc.). These types of models also give an idea about how an individual understands and represents the relation between the model and actual modeled object

(e.g. size-ratio relationship) 3) Syntactic model, which is structured based on similarities (such as Bohr's atom model-solar system, Coulomb's law and Newton's gravitational law, etc.). Syntactic models could be very useful to grasp ideas based on their similarities. 4) Hypothetical-deductive models do not have any immediate relation with the real observable world (such as nanoscale particles, electron's motion, thermodynamic, etc.). These types of models are deemed to be quite abstract for younger age children and they may have hard time embodying hypothetical models into physical models (Lehrer & Schauble, 2000).

Model-based reasoning is a good foundation for conceptual change, in comparison to traditional perspectives of reasoning such as reasoning by analogy (Nersessian, 1999). The problem-solving process also can be enriched and promoted to be more creative via model-based reasoning (Nersessian, 1999). In their study, Sun and her colleagues (2006) used model-based reasoning in real world problem solving situations. To help students develop model-based reasoning, the facilitators encouraged students to use whatever visual models such as abstract hypothesis, physical models, diagrams, tables and matrices, which provide all the information to compare and analyze. With limited help and instructions, students seemed to gain sturdy understanding and problem-based learning (PBL) via model-based reasoning. Furthermore, their perception of model-based reasoning and modeling techniques positively changed after engagement with the modeling process as part of PBL. Many researchers emphasize that there is a strong correlation between model representation and conceptual change (Lehrer and Schauble, 2006; Nersessian, 1999, 2002). Students are exposed to different ways of representation in math (graphs, equation, tables, Venn schemas, etc.), in science (pictures,

simulations, physical models, etc.), and in social science (outlines, maps, timetable, etc.) courses from k-12 and college. Based on the course of learning, learners may transfer one way of representation to the other to reinforce and use their understanding of the phenomena.

Raghavan and Glaser (1995) designed the Model-Based Analysis and Reasoning in Science (MARS) curriculum to examine conceptual understanding of “balance of force” with six-grade students. As part of the MARS curriculum, the researchers used interactive computer programs and dynamic (hands-on) representations to visualize abstract phenomena. After implementation, the authors found out that the MARS curriculum takes up more time to cover the same topics than traditional curriculums. Students started developing skills for spontaneous usage of models to share their ideas while others still need to be reminded to use models. Furthermore, students tended to see models as copies of actual phenomena at the beginning of the curriculum, but toward the end they changed their idea of a model to be more of a tool which can be used to predict, evaluate, and test the ideas.

Application to the Current Study

In this study, students’ reasoning used to construct new knowledge and represent existing knowledge is our focus point. I closely investigated how students conceptualize fundamental quantum mechanics concepts by using models that properly relates these concepts to each other as a main source of their reasoning. In addition, engaging with computer-based simulations is assumed to be helpful in visualizing and conceptualizing basic quantum concepts, but a significant amount of research showed that it might not be effective without the support of hands-on activities and well-organized instructions

(Abdulwahed & Nagy, 2011; Clark, 1994; Sarabando, Cravino, & Soares, 2014).

Therefore, I believe computer simulation itself does not provide students with a deep conceptual understanding and expert-level reasoning skills. To improve students' understanding of abstract quantum mechanics concepts, an instructional module which was enriched by integrating different types of models such as physical manipulative, mathematical models, and graphical representations besides computer simulation was employed in this study.

Model-based reasoning as a theoretical framework helps to combine individual's subjective/intuitive knowledge with scientifically and mathematically proven knowledge (Lehrer, Horvath & Schauble, 1994). Model-based reasoning is a method that provides a lot of information about conceptual change (Nersessian, 1999). Hence, providing a cognitive foundation to develop and practice reasoning via models facilitates learners to render and construct their understanding in meaningful chunks. With this in mind, Model-based research has been chosen as theoretical and part of the methodological framework guide through this research. Considering the significance of models and model-based reasoning, many researchers have suggested and studied the integration of models in inquiry –based learning in natural science education curricula which they called model-based inquiry/learning (Clement, 1989; Clement & Ramirez, 2008; Giordan, 1991; Halloun & Hestenes, 1987; Heller & Reif, 1984; Hestenes, 1987; Kaput, 1991; Kindfield, 1993/1994, 1994; Louca & Zacharia, 2012; Maia & Justi, 2009; Nersessian, 2009; Raghavan & Glaser, 1995; Stewart et al., 1992; White, 1993). Instructors use models to assess students' thinking which also gives an important

information about how teaching /learning strategies and materials are benefiting students and what needs to be improved (Lehrer & Schauble, 2000).

2.2.1 Model-Based Learning (MBL)

According to National Research Council [NRC] reports, *How people learn*, (1999) and later the next generation science standards (NGSS, 2011), students should be encourage to understand scientific concepts via inquiry and personal engagement with scientific practices instead of directly learning scientific facts, or they should use inquiry as part of the process. Likewise, inquiry-based learning and hands-on engagement have been found positively correlated with undergraduate students' understanding of natural science concepts (Carlson & Sullivan, 1999; Gormally, et al., 2009; Haskett, 2001; Nersessian, 2009; Zollman et al., 2002). Moreover, cognitive science studies argue that all scientific developments occur when scientists construct their reasoning as a result of their inquiry on observable evidences and theoretical insights use some sort of representation to make sense of the scientific concepts (Nersessian, 2009). With the fact that model-based inquiry provides a sufficient environment for inquiry-based learning as well as an opportunity to develop variable representations of scientific phenomena, it has a broad application in natural science curricula. A number of studies have been conducted with groups of students of different ages by integrating model-based learning into their current curriculum.

Current Studies about Model-Based Learning (MBL)

Observing change in students' models can be very difficult because there are many factors hidden under their cognitive structures and we cannot directly observe how

their sense-making process functions (Clement, 2000). Each stage of model revision gives many clues about the current cognitive level of the individual. For example, Buckley (2000) conducted a case study about a 16-year-old biology student's model change process before and after interacting with 'Science for Living: The Circulatory System' (SFL) which was enriched with interactive multimedia resource. The student started with an initial heart model and altered her model based on sequential questioning, inquiries, interactions with the teacher and researchers. Buckley recognized that previous models helped the student create new questions, organize pieces of information and build a new model. After passing through many model-alteration stages, the student who engaged in a model-based learning curriculum showed significant improvement in her understanding of the cardiovascular system. She was also able to use her model to transfer her knowledge to explain real life phenomena such as by-pass surgery.

Model-alteration stages may show differences from individual to individual based on the initial model, previous experiences and prior knowledge (Giere, 1994; Snyder, 2000). Snyder (2000) studied 27 novices (9 undergraduate students who completed introductory level classical mechanics course), intermediate (9 first or second level physics graduate students) and expert (9 physics professors) level subjects to compare how individuals in three different expertise levels use theory- or model-based categories when they categorized 18 physics problems. He claims that experts tend to use a more theory-based approach when they solve problems in comparison to novices, since novices cannot see the problem as a whole with its details. On the other hand, novices utilized a more model-based approach when they categorized physics problems, while intermediates used a mix of theory and model-based approaches. Snyder asserted that the

reason novice students had more model-based explanations than experts or intermediates was because the questions in the study were mostly abstract and not similar to real life examples or models that were included in the textbook. Therefore, novice students could not make the connection between the real-life situation and the problems and likewise could not figure out the theory behind the phenomena. These results support the notion that there is a pattern between an expert, novice, and intermediate individual's level of benefit from the model-based approach.

A student's model informs instructors or curriculum developers about a student's way of thinking. Knowing students' ways of thinking can also inform instructors about how to plan their lesson, prepare materials, and design facilitating activities. In a study with 7th grade mixed ability and 11th grade honors students, Grosslight et al. (1991) asserted that students may have three different levels of understanding of models. Novice students (7th grade mixed-ability) mostly considered models as a copy of real objects or phenomena although they are aware of the differences between models and reality. Students who were more knowledgeable about models can make the separation between models and real world phenomena. They can see the limitation and similarities of the models after looking at experimental evidence and they can discuss how to revise the models to overcome limitations. Finally, experts understand that models serve as a tool to develop, test, and evaluate the ideas.

Raghavan and Glasser (1995), on the other hand, were mainly interested in promoting students' qualitative reasoning, since prior research demonstrated that most of the time inquiry-based science curriculum developed by teachers did not encourage students to use their reasoning to learn descriptive concepts (Larkin, 1981). The authors

argued their motivation to focus on qualitative reasoning for two reasons. The first reason is that poorly developed instruction may yield students who construct inappropriate qualitative models and incomplete understanding. The second reason states that students come into science classrooms with existing models that are based on qualitative concepts. These models can be used as pedagogical tools to support qualitative understanding. Therefore, Raghavan and Glasser (1995) initially revealed students' prior mental models and used them as a baseline for further models built by students after engaging in computer-based visualizations. In this case, computer-based simulations provided active learning environments that helped students improve their observations and predictions to a more sophisticated level.

A typical model-based learning environment is defined to be student-centered and highly interactive. Students are supposed to engage in different representations of a modeled phenomenon (object) via hands-on activities, physical models, interactive computer programs, mathematical models, free-body diagrams, etc., which offer students different perspectives of the same phenomena. That will provide an opportunity for the instructor to both present the phenomena (or objects) with all their possible features and also point out the limitations (if they exist) of using a model, which may cause a misunderstanding of the real world. Since a model-based learning environment requires that students be responsible for their own learning, teachers are not expected to directly intervene with students' learning but encourage them to be more active in terms of manipulating models, engaging with different perspectives of phenomena, and explaining their understanding.

Quantum phenomena are mostly very difficult to model. Scientists perform thought experiments in quantum studies to simulate a real experiment by using their imaginations. Also, current studies reveal that thought experiments are still commonly used by contemporary scientists (Clement, 2002; Trickett, & Trafton, 2007). In fact, different researchers use different terminology for the process that I described as “thought experiment” above. The main ones are mental experiment, mental simulation, what-if, and inception (Trickett & Trafton, 2007). Kenneth Craik (1979), who is one of the pioneers for the concept of the “*Mental Model*”, asserted that individuals generally continue running experiments on their internal models. The possible reasons for conducting thought experiments are 1) it may not be possible to set up a real experiment, 2) there might be a chance to contrast both imaginary and real experiments.

Research about Model-Based Instruction in Science

Science is an entity that shows its effects and products in all facets of our lives (McComas et al., 1998). New perspectives of science have changed the focus from experimentation to creation, testing, refining, and revision of models (Lehrer & Schauble, 2010; National Research Council [NRC], 2007). Hence, scientists started using models to make explanations and predictions about data (Gilbert & Bolder, 2000; Gobert & Buckley, 2000; Passmore et al., 2009), to test and evaluate hypotheses, as well as to prove or disprove theories. Although different disciplines of science use different methods and approaches to practice science, in general, creating and refining models is considered a part of the scientific process (Lehrer & Schauble, 2006). With the process of combination and reasoning of the operational models, scientists are able to construct scientific theories (Giere, 1988; Passmore et al., 2009). Correlatively, model-based

reasoning can be a very effective tool in the learning process (Pirnay-Dummer, Ifenthaler & Seel, 2012).

Students mostly bring existing models that have been constructed based on their previous formal education or daily experience into the classroom (Yuksel, 2011). These models may or may not be accurate in terms of ontological perspective; however, students use these models to make sense of new knowledge in the decision making process. Many researchers claim that well-designed model-based instruction enables students to revise their models, modify or change, if necessary, and make their models more complete thereby matching better to the real model (Clement, 2000; Gobert & Buckley, 2000; Hanke, 2008). With that in mind, educators and researchers have developed an interest in utilizing model-based design to generate 'educational innovations' (Pernaa & Aksela, 2013) as well as a theoretical framework.

Passmore and her colleagues (2009) demonstrate the process for using models in scientific inquiry in their diagram (see Figure 2.2). In this diagram, models are the center of the process and have reciprocal relationships with data patterns in terms of developing and explaining those patterns. The data pattern in the diagram from Passmore and her colleagues (2009) is isolated from phenomena, but it is connected indirectly via explanations.

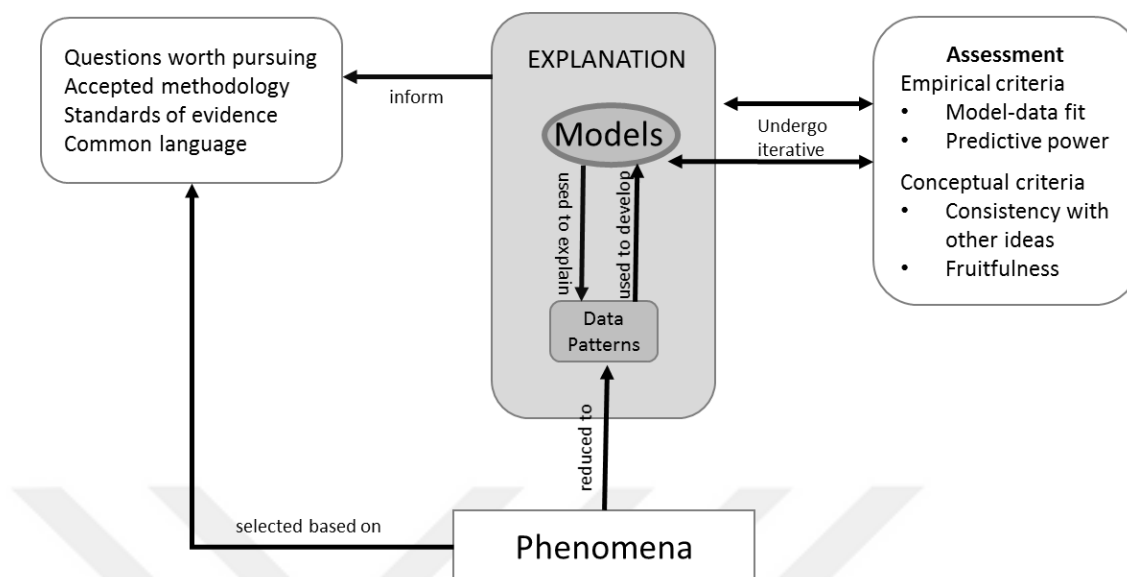


Figure 2.2: Model description diagram (adopted from Passmore et al. (2009))

The research done on scientific work also indicates that the use of models in scientific communication has increased (Nersessian, 2005; Windschitl et al., 2008). To assist understanding of the process, and demonstrate scientific discoveries, scientists have been using visuals such as graphs, drawings, pictures, diagrams, and computer simulations (Latour, 1990; Windschitl et al., 2008).

Application to the Current Study

While a significant argument about the need for a new approach has been propounded in quantum mechanics courses, researchers frequently utilize computer-based simulations as one of the most important sources for interactive teaching/ learning purposes. The main concern of teaching physics, particularly quantum mechanics, is that it can be abstract and deal with non-observable phenomena. With existing tools, some physical concepts still cannot be demonstrated or modeled. Particularly in quantum

courses, it is not easy to simplify concepts with models and mostly impossible to have students make direct observations of phenomena (Mannila, Koponen, & Niskanen, 2002). At this point, using a computer simulation becomes a convenient source to simulate real cases and predict different aspects of the case when conditions changed. Besides being an easy tool for dynamic visualization, computer simulations also serve as a facilitator to access information, inexpensive assistance and patient tutors.

The fundamental philosophy of constructivist learning is an active engagement of the learning process and meaningful construction of one's own knowledge based on personal experiences (Sjøberg, 2007; Taber, 2006; Von Glaserfeld, 1984). Based on a constructivist perspective, individuals learn better when they actively inquire of the learning materials, try to find solutions to problems, and build the new knowledge piece by piece. Computer-based simulations and physical models offer learners a dynamic portal where variables in the system can be manipulated by users to test and refine outcomes. To enhance scientific reasoning, systematic and critical thinking, interactive simulations have proven to be quite effective (Lindgren & Schwartz, 2009). Students develop or revise their models when they see visual models either hands-on or given in the simulations (McKagan et al., 2008). Furthermore, learning via the aid of computer simulations is considered "scientific discovery learning," which branched out of constructivism (De Jong & Van Joolingen, 1998).

Another important aspect of using computer-based simulations and physical models in education is the motivational factor in students' engagement. In recent times, interactions with computers in every field of life have become routine. People actively use computers for calculations, graphical representations, information searches, and

leisure gaming (Vogel et al., 2006). Hence, using computers in educational settings may increase students' interest and motivation to take action in their learning (Rieber, 1996; Romme, 2003; Vogel et al., 2006).

Research that showed the importance of modeling and model-based learning in understanding science concepts motivated some researchers to take advantage of using models in teaching different quantum mechanics concepts (Muller & Wiesner, 2002; Petri & Niedderer, 1998; Zollman et al., 2002). Although it was not clearly stated that they used model-based learning/inquiry in their instructional design, these researchers appeared to support their learning materials with visual and physical models.

2.2.2 Challenges to Teach Quantum Mechanics and Attempts to Use Models in QM Instructions

Historically, the instructional approaches for teaching quantum concepts have had many limitations in facilitating students' understanding of the behavior and features of subatomic-level particles and their implication in the classroom (Muller & Wiesner, 2002). Unfortunately, traditional or transmissive instruction does not offer learners much more than passive listening and memorization of information given by the instructor. Decades of research on students' learning of science have shown that transmissive approaches are ineffective (Brown, 2004). Transmissive approaches often result in students' failure to reflect their own thinking, to recognize the relationship of developing robust mechanistic understanding, and to construct their own understanding of concepts (Brownlee, 2001; Tickle et al., 2005). Therefore, it is necessary to develop instruction that aligns with decades of research on how students learn so that we can better facilitate students' learning of quantum mechanics.

There are also some disagreements about how quantum mechanics teaching would be more effective. Some educational researchers support the idea that quantum mechanics understanding can be built on students' classical mechanics knowledge. Others say students' knowledge of classical mechanics prevents them from transferring their perceptions from a deterministic to a probabilistic view, so we need to avoid referring to classical mechanics when teaching quantum mechanics. Olsen (2002) indicated that a student's classical "worldview" has a very strong and negative effect on quantum mechanics learning. He also believes the terminology used in classical mechanics and quantum mechanics is very different and when the same terminology is used for the phenomena (both in quantum mechanics and classical mechanics), it will be misunderstood and hard to correct by students.

In addition to considering learning difficulties, there is another important point in quantum mechanics learning: shifting lenses to look at quantum phenomena. As mentioned above, the particles in a quantum level have very different properties and behaviors than macro or even micro level objects. For this reason, in order to understand how these objects behave at the quantum level, students should be encouraged to approach quantum concepts with a more creative and open-minded perspective. The idea of the non-existence of absolute truth in the quantum world should be emphasized very carefully during the instruction. For example, the uncertainty principle does not allow one to determine the exact location and momentum of an electron at the same time. If one of the quantities is known with high precision, the other quantity is known with less precision. In classical physics, on the other hand, everything can be measured with almost infinite precision in principle. Teachers should emphasize the distinction between two

ways of thinking in quantum mechanics and classical physics. Shiland (1997) states five strategies in conceptual changes: “1) The students become aware that their current conceptions cannot address a particular problem; 2) The students’ opinions are further developed and clarified through demonstrations, experimentation, and questioning; 3) The students’ opinions are shown to be inadequate; 4) New concepts are introduced which are shown to solve the problem; and 5) Further applications of the new concepts are demonstrated” (p.537). When students are put in a situation and they realize that their classical way of thinking way does not solve the problem in quantum mechanics, they should involve a hands-on activity, followed by critical thinking and searching for a better explanation, then qualified learning will occur.

Another way to help the students’ understanding process is to provide them with an historical and philosophical perspective and how that plays an important role in scientific development (Justi & Gilbert, 2000). When students know, for instance, an early scientists’ way of thinking about atomic structure and their experiments, they have an opportunity not only to understand the evolution of the knowledge about atomic theory, but also to realize that famous scientists started with simplistic approaches to solve the problem and then ended up with a very sophisticated solution by revising and refining their approach without giving up (Tsaparlis, 1997).

Niedderer and his colleagues (1997) used a computer tool called STELLA to simulate Schrödinger equation and help high school students’ model building process. Their primary goal was introducing the concepts of “state” and “orbital” by using the analogy of standing waves in one, two and three dimensions. They also intended to reduce the mathematical formalism.

Petri and Niedderer (1998) studied the learning pathway of a high school student throughout a quantum physics course. Their study was designed as application of Niedderer et al. (1997)'s instructional tool. During the course curriculum, atomic models were learned based on the Schrödinger equation. The student's initial model was "the planetary model". The authors called this model "the initial state of the cognitive element atom" (p.1080) because it was deeply rooted in the student's cognitive system via prior lessons. In the second stage, the student had "the probability orbit model" after covering photoelectric effect, electron detracton, and the uncertainty principle. In this model, he still carried on the orbital notion, but he also combines this with the idea of wave function, which is concentrated on the orbit. In the next stage, the student had "the state-electron model" which eliminates the notion of "particle" from the quantum model of the atom. That model indicated the impossibility of finding particles at a certain location. The final stage illustrates that the student had "the electron cloud model" which includes "several conceptions co-exist and are connected to form different layers of the cognitive system, with a metacognitive layer on top" (p.1083). In general, the quantum concepts developed in all stages were different from what the teacher proposed.

Muller and Wiesner (2002) tried to find out how students could be taught quantum mechanics beyond traditional instruction and classical mechanics, because they believe that most of the misconceptions and learning difficulties originate from traditional methods of instruction. In the study, students have explored the conceptual perspective of quantum mechanics in the first part of the course called the "basic course" and the formalism perspective of quantum mechanics in the second part called the "advanced course" in the light of research-based learning design. In this study,

researchers assigned students to two different groups. One group received treatment instruments which included simulations and text that researchers developed. The other group received traditional instruction. The findings of the study demonstrated that most of the treatment students acquired a satisfactory understanding about quantum mechanical concepts. They also overcame some of the misconceptions they gained via traditional instruction. Furthermore, the treatment group refused the deterministic approach in quantum mechanics while the control group still had some doubts.

Zollman and his colleagues (2002) tried to examine if non-science high school and first year college students can understand quantum mechanics without classical mechanics learning. They developed an instructional design for quantum mechanics that was called *Visual Quantum Mechanics- The Original* which includes hands-on activities and computer-based simulation. The quantum mechanics concepts covered in the instructional materials were Solids & light, luminescence, waves and wave functions, quantum tunneling and potential energy diagrams. As a result of working with many students in high schools and universities worldwide (approx. 175 teachers in 160 schools), they found that the learning materials promoted understanding abstract quantum mechanics concepts for both students who had limited or none science background and students who had strong science background. They also claimed that hands-on activities improved the interaction between students-students and students-instructors.

Another recent work has been conducted by Olympiou and Zacharia (2012). In their research, they examined 70 undergraduate students conceptual understanding of light and color concepts in three different conditions. In the first condition students used only physical manipulative (N=23). In the second condition, students engaged with only

visual manipulative (N=23). The last condition was designed as mixture of both manipulative (N=24). All students in three different conditions received the similar inquiry-based curriculum and took pre- and post-tests before and after the implementations. The analysis of students' responses indicated that students who engaged with both physical and visual manipulatives performed better in the post-test than students who were in only physical and visual manipulative conditions.

The findings from Olympiou and Zacharia (2012) and other researchers who utilized multiple models in their curriculum to teach quantum mechanics concepts support the idea of different model exposure make students to think about different perspectives of the same phenomena/object and grasp the essence of the idea as whole.

2.3 Current Studies about Quantum Mechanics

Human beings have always been in search of the nature of the world, universe and the working mechanisms therein. Therefore, starting from ancient philosophers, scientists have been seeking the “absolute truth” about the external reality by asking questions (Kuhn, 1962, 1970).

In the early twentieth century, scientific revolution in physics came into prominence with a radical turning point in the way of approaching the phenomena (Muller & Wiesner, 2002). When all the efforts done to understand the atom and its component via classical (deterministic) framework came to a dead end, scientists started to propound new theories that were not compatible with the existing conventional epistemology, and they supported their theories with mathematical arguments. Even though the rise of quantum mechanics opened the gates of a mysterious universe, there are still many unknowns of the quantum world for people due to its complex and abstract

features. Regarding the difficulty of understanding quantum mechanics, Richard Feynman, one of the greatest physicists of our time, said, “If you think you understand quantum mechanics, you don't understand quantum mechanics.” With this statement, he pointed out the sophisticated and probabilistic feature of quantum phenomena (Singh, Belloni, & Christian, 2006). However, it is now very important to understand at least the fundamental concepts of quantum physics such as photons, the quantization of light, the photoelectric effect, the quantization of matter, the Bohr model of the atom, wave-particle duality, development of modern quantum mechanics, etc., and take advantage of them. Today, we are living in a world that uses high technology in every field of life. Therefore, developments in science and technology require more attention on learning modern physics concepts to be able to follow the new era's technology and to create more qualified scientists and engineers (Steinberg, Wittmann, Bao & Redish, 1999).

The biggest challenge in teaching and learning quantum physics in high school, and even college level, is the abstract nature of the concepts (Johnston et al., 1998; Zollman et al., 2002). The different behaviors of subatomic level particles do not allow them to be perceived as macro level objects that can be explained with Newtonian physics (Hurwitz, Abegg, & Graik, 1999; Ireson, 2000; Mashhadi & Woolnough, 1999; McKagan et al., 2008). Therefore, there are significant distinctions between classical mechanics approaches and quantum mechanics approaches. One of the difficulties in students' learning quantum mechanics arises from the indistinct line between these two different approaches. In quantum or modern physics courses, teachers tend to use traditional instructional methods that create obstacles for students to achieve transition

from a deterministic to indeterministic perspective (Mashhadi & Woolnough, 1999; Muller & Wiesner, 2002; Olsen, 2002).

There are a number of research projects that investigate students' understanding of quantum mechanics concepts such as the photoelectric effect, wave-particle duality, the double slit experiment, the uncertainty principle, conductivity, wave function, etc. (Muller & Wiesner, 2002; Olsen, 2002; Shiland, 1997; Singh, Belloni, & Christian, 2006; Wittmann et al., 2002; Zollman et al., 2002). Most of these studies were conducted with college level physics and engineering students since the content of quantum mechanics is considered expert-related. On the other hand, many researchers also agree that high school is the best place to give a broad sense of science knowledge to all students, including those who will choose physics and engineering as a career pathway and those who will not choose a field related to science (Johnston et al., 1998; Muller & Wiesner, 2002; Steinberg, et al., 1999). Hence, it is an opportunity for students who will major in physics and engineering to be prepared for future sophisticated learning, and also an opportunity for students who will not major in physics to learn some cutting-edge concepts such as quantum physics, which will shape the future of technology.

Studies targeting high school students generally focus on conceptual understanding of some quantum concepts rather than mathematical formalism. For example, in the Olsen (2002) study, high school students were asked to answer a multiple-choice and open-ended questionnaire that consists of questions from different parts of the quantum mechanics curriculum. Of these questions, they analyzed students' responses relating to the dual nature of light and electrons. After analyzing those responses, they found that students could not comprehend that light and electrons have

similar natures even though these concepts were taught during lessons and exist in textbooks. The majority of students perceived that electrons behave as particles while light has a dual nature. Students also failed to understand some abstract concepts, like calculating the wavelength of an electron, for example.

Fanora, Otero, and Arlego (2008) used a different teaching method to help students' conceptual understanding. The basic quantum mechanics concepts such as probability distribution, amplitude, Planck's constant, and classic quantum transition were taught to high school students with the assistance of the proposed conceptual structure teaching (PCST). PCST is basically described as "a set of concepts, the relationships between them, knowledge claims, principles, situations, and explanations related to a certain conceptual field, that the teacher must reconstruct based on a Conceptual Structure of Reference (CSR)" (p.38). The analysis of students' final test performance demonstrated that many students had difficulty understanding that electron motions can be depicted via a wave function, but they were able to explain the interference pattern in the double slit experiment and recognize the existence of a wave function for both macroscopic and microscopic objects. Another study conducted by Griffiths and Preston (1992), revealed fifty-two misconceptions about the characteristics of atoms and molecules. The result of interview responses with thirty high school students demonstrates that students still held a classical view of the atom and they use the solid sphere shape model to represent an atom. Students also expressed that atoms are made only of electrons, protons and neutrons, but nothing else. The size and weight of atoms also seems quite confusing for those students.

Quantum mechanics involves the combination of mathematical formalism with physical phenomena. In other words, mathematical manipulation is a significant part of quantum conceptualism (Singh, 2007). For instance, in order to understand how the wave function of a physical system evolves over time, one needs to solve time-dependent Schrödinger equation or look for matrix mechanical solutions. Therefore, a strong background in calculus-based mathematics is a prerequisite for a robust understanding of advanced quantum mechanics (Pospiech, 1999). Consequently, students who fail to connect conceptual ideas to mathematical formalism may not acquire an adequate and meaningful understanding in quantum mechanics (Tsaparlis, 1997). Mathematical formalism in quantum mechanics is rooted in a very advanced level of calculus-based mathematical knowledge. Therefore, it is believed that teaching quantum mechanics formulation is beyond high school curriculum. Michelini, Ragazzon, Santi and Stefanel (2000) claim that there is no advanced mathematical skill to teach in elementary introduction to quantum mechanics.

Hilger et al. (2012) argue that physics content taught in high school is not compatible with currently developed science and technology. Therefore, they aimed to develop a way to teach quantum mechanics in order to make a connection between a quantum curriculum and current science and technology content. They conducted a study with four different third-year high school classes to examine their learning progress during the teaching process. Quantization, uncertainty principle, state, and superposition of states concepts were introduced by avoiding giving advanced level mathematics formulations. Students were required to complete eight steps throughout the quantum lessons. These were: developing a mind map in pairs; reading an article and developing

free-choice material, watching a documentary and developing second round concept maps with the same pairs, comparing the mind map with the concept map in pairs and writing a report, large group discussion about drawings and quantum concepts, summative and formative assessments, and oral analysis of students' performance, teaching strategies etc. The authors found that the students improved their concept maps in comparison to the mind maps after quantum mechanics instruction. The connection between concepts and organization of knowledge seems to be understood by some students. They realized the hierarchical relations between the concepts. Some students also thought that atomic physics is a subject of classical mechanics, and classical mechanics leads quantum mechanics. Tsaparlis and Papaphotis (2009) carried out a study to find out students' understanding and critical thinking about atomic and molecular orbitals, and their conceptual change was reported. 12th grade students took a written questionnaire first and then a portion of them attended a semi-structured interview as individuals or in small groups. The authors claimed that the Bohr atom is still a predominant model in the students' minds. In fact, sixth grade textbooks reinforced this idea with definitions such as "electrons are constantly moving around the atomic nucleus in a strict arrangement on orbits" (Alexopoulos, Therianos, Conostas, & Florakos, 1996, p. 9, as cited in Tsaparlis & Papaphotis 2009). Students were taught this idea until 12th grade where they are introduced to the quantum mechanical atom model for the first time, however, the quantum model cannot replace the rooted Bohr model easily. According to Tsaparlis and Papaphotis (2009), these types of models are not misconceptions, but they are old models that demonstrate the earlier scientific models.

Challenges of quantum mechanics in high school is not only limited to students. Physics and Chemistry teachers also have difficulty understanding concepts related to quantum science and the relationship of those concepts to many of the topics included in the high school science curriculum (Robblee et al., 1999). Robblee and his colleagues (1999) indicated that if these teachers were trained to use innovative instructional materials such as computer simulations, their self-confidence would increase and their communication with students would be proportionally more fruitful.

The majority of educational research in quantum mechanics has been concentrated on college-level students. A remarkable amount of those studies reveals that first- or second-year students of physics or engineering pass the modern physics courses with a lack of understanding or with significant misconceptions. (Akarsu et al., 2011; Sadler & Tai, 2001; Wittmann et al., 2002). College students' conceptual challenges vary from atomic structure to advanced quantum theories. Most students lacked a conceptual understanding of quantum theories despite the fact that they could solve complicated quantitative problems. Surprisingly, research also showed that, similar to high school students' perceptions, many college students also hold on to Bohr's atom model insistently (Broklova & Koupil, 2006; Muller & Wiesner, 2002).

In a quantum mechanics curriculum, unfortunately, students are inundated with experimental details (Niaz et al., 2002) and heavy mathematical calculations which cause students to fear quantum concepts and resist further learning. Niaz et al. (2002) investigated how freshmen students who are given an opportunity to discuss and revise quantum phenomena with their group mates perform better in comparison to students who are passive listeners. Interactive discussion has proven to increase students'

motivation, learning/understanding and attention (Chinn & Anderson, 1998; Niaz et al., 2002; Resnick et al., 1993)

Johnston and his colleagues (1998) conducted research with college students to reveal mental models of students who passed a quantum mechanics course and surveyed successfully. That survey covered the quantum mechanics topics of wave-particle duality, the nature of eigenfunctions, potential wells, and operators. The results of students' responses showed that most of the students used some terminology that was not related to what was asked in the questions. Additionally, the terminology that they used indicated that learning occurred only on a surface-level. The authors asserted that these results were because of the fragmented nature of students' mental models.

Another study on a first year college students' conceptual challenges about atoms and molecular orbitals was conducted by Tsapalis (1997). They analyzed students' responses on the end-of-course exams. Most of the students could not give a definition of the atomic orbit. Some students gave a textbook definition of atomic orbitals, which is a region in space where electrons exist with 90% possibility. The mathematical function for hydrogen-like atoms was well known among students while the Schrödinger equation solution was only utilized by a few students. Similarly, students' performance in answering questions about molecular orbitals was very poor.

The behavior of light is another challenging quantum concept for students (Ambrose et al., 1999; Steinberg et al., 1999). Therefore, Steinberg and his colleagues (1999) attempted to understand how students use their classical mechanics knowledge when they learn quantum mechanics. The authors claimed that some of the basic phenomena of quantum mechanics such as the wave properties of matter, atomic

spectroscopy, and the dual nature of light cannot be understood if students do not know waves, diffraction, interference, and superposition concepts from classical mechanics. After analyzing classroom observations, open-ended and multiple-choice responses, videotape and interview responses, they reported that students could not state the amplitude of a light wave is electromagnetic. They also used the term “fitting” or “not fitting” when they explained the single- and double-slit interference. While some students drew a photon passing through the single-slit in a sinusoidal path, other students showed waves as a spatial entity.

The reason for the common misconceptions, according to Styer (1996), is that quantum learning does not have a direct application in everyday life. He argues that while students may have preconceptions about classical mechanics concepts, which can be observed and experienced in daily life, in quantum mechanics they could not have preconceptions because it is not possible to see any quantum phenomena in daily life. Although it is commonly accepted among students that physics is directly relevant to real-world phenomena, it is difficult for them to see direct application of physics in their immediate experiences. (Redish, 2004). Besides that, students develop some misconceptions for of variety reasons. Styer (1996) stated fifteen common misconceptions held by college students. These are mostly about Eigen states, quantum states, wave functions, measurement of particles parameters, etc. According to Styer (1996), these misconceptions give a clue about students’ understanding mostly in operational and conceptual levels, and they can be corrected via well-structured teaching design.

Singh (2001) indicated that another reason for the misconceptions is the insufficiency of courses students took previously. On the other hand, Hurwitz, Abegg, and Garik (1999) claim that students cannot understand quantum mechanics since they are unable to visualize three-dimensional models in their minds; they lack a sophisticated perception, and are unable to think from many perspectives. Additionally, vague wording of some text material leaves students unable to discern the correct definition for a particular condition (Cervellati & Perugini, 1981). Duit and Treagust (1995) argued another important mistake of educators and students is that students have (or have been forced to have) the bad learning habit of memorizing many names, equations, formulas, or descriptions without really understanding the logic behind these formulas or descriptions. For example, they said that if students are given the Schrödinger equation to solve, they can solve it without any hesitation, however, when they are asked to explain what is being represented, they cannot give a clear explanation. This inappropriate learning habit can be reduced if students are encouraged to take an active position in their learning. Many researchers have tried to answer the question “How do people learn?” The common ground that almost all of them have consensus on is that individuals learn best when they actively construct new knowledge piece by piece on their prior understanding (DuFour et al., 2006; McKagan et al., 2008; Zollman et al., 2002). When learners have ill-constructed knowledge, it is not easy to help them change and reconstruct scientifically appropriate knowledge (Confrey, 1990; diSessa & Sherin, 1998). A growing body of studies emphasize the importance of determining students’ misconceptions and learning difficulties first and then helping them to reconstruct their

understanding based on proper scientific models via new student-centered strategies (Driver & Easley, 1978; Duit & Treagust, 1998; Slotta & Chi, 2006).

Broklova and Koupil, (2006) stated that the spatial probability density of hydrogen atom eigenstates is quite difficult for students to visualize. To facilitate second year university students' construction of a conceptual model, they used interactive tools designed by the research team. The interactive tools helped students to visualize wavefunctions and probability densities via the aid of graphs. The program called *Workbook* provides a platform for students to engage with activities. Students' different representations of the same wavefunction helped them to grasp the concept broadly. Moreover, students who used the new interactive tool found it very interesting and fun. The only drawback of the tool mentioned by students was time spent to finish the activities.

2.3.1 Need for New Approaches in Quantum learning

The nature of understanding and learning has always been a subject for many learning theorists (Ausubel & Robinson, 1971; Fensham, Gunstone, & White, 1994; Mintzes, Wandersee, & Novak, 1988). For many years, lectures were used as the main instructional approach (Omelycheva & Avdeyeva, 2008). It is still commonly preferred among college courses due to inexpensive and extensive access. In an average college, general natural science courses have over a couple hundred students registered each semester. Therefore, instructors can teach rich context in a short time to many students via lectures, however, they cannot make sure every student actually learns the materials (Omelycheva & Avdeyeva, 2008; Wood, 1989). Current literature suggests that one of the best ways of learning is a student's active engagement in their learning (DuFour et al.,

2006; Prince, 2004; Zollman et al, 2002). During active learning, students are able to process every step that they do and give an output of learning. In that way, consistent and long-term learning can occur.

While physics, in general, is difficult to grasp via a lecture and textbook-based approach, dealing with quantum mechanics concepts is almost impossible for the majority of students (Fischler & Lichtfeldt, 1992; Michelini & Stefanel, 2008; Niedderer, & Deylitz, 1999; Zollman, 1999). Many of the traditional teaching methods used to teach classical mechanics do not meet the requirement for teaching quantum concepts (Mazur, 1997). In fact, current research supports that students at different age levels have incomplete or inconsistent conceptual knowledge of quantum mechanics (Bethge & Niedderer, 1996; Fanaro, Otero & Arlego, 2009; Griffiths & Preston, 1992; Johnston, Crawford & Fletcher, 1998; Singh 2001; Wittmann, Steinberg & Redish, 2002). Unfortunately, although many college level instructors are experts in content knowledge, in terms of effective teaching and creating an active learning environment, there is much room for improvement. They mainly emphasize the products of science and experiments; yet fail to notice the development process of scientific knowledge (McComas & Almazroa, 1998).

All efforts to figure out what is the best way of teaching/learning quantum concepts show that new instructional design, teaching methods, and activities are indispensable (Olsen, 2002). Therefore, many researchers concluded that new instructional methodologies should be developed and implemented concerning students' cognitive abilities, backgrounds, and learning processes (Niedderer & Deylitz, 1999; Olsen, 2002; Zollman, Rebello, & Hogg, 2002). In fact, researchers have been using

different strategies including a new approach for teaching (Niedderer & Deyliz, 1999), hands-on activities (Zollman, Rebello, & Hogg, 2002), and computer visualizations (Hurwitz, Abegg & Garik, 1999; Robblee, Garik & Abegg, 1999; Singh, 2001), etc. These studies have been conducted to examine higher-level students' quantum mechanics learning. All of them suggested that using innovative instructional methods to teach quantum concepts somehow improves students sophisticated thinking skills as much as it helps them understand these complex concepts. However, there is still a lack of literature as to what the most challenging concepts in fundamental quantum mechanics topics (such as atomic structure, energy levels, and atomic spectrum) are; and how a well-structured model based learning environment facilitates students to overcome these challenges.

Application to the Current Study

In light of this perspective, learners' experience and constructed reasoning cannot be discarded when dealing with learning difficulties and further learning. Even though quantum mechanics is seen as a non-related topic for everyday life, there can be many different observations or effects that are results of quantum effects of particles (e.g. propagation of light in different mediums, radar systems by using Doppler Effect, laser, usage of a PET scan machine in medicine, computer systems, etc.). Knowing students' models and challenges about quantum physics helps to guide development of instruction designed to improve students' understanding, attract their attention, and counteract the stereotypes regarding its difficulty or impossibility. Moreover, when students are encouraged to construct, review, and evaluate their models, their conceptual development and understanding are positively affected (Abell & Roth, 1995; Coll, France & Taylor, 2005). Hereby, model-based inquiry/learning offers learners the ability to connect

conceptual information with metacognition through the agency of inquiring physical models (Penner et al., 1997).

Model-based learning theory utilized in this study is inspired from the work in Clement's (2000) study. His framework provides a chain of time-slots which represents an individual's learning process and model change phases. To monitor the change in students' models and to organize model-based activities, which were developed based on facilitating students to gradually improve their model, I will be using Clement (2000)'s framework shown in Figure 2.3.

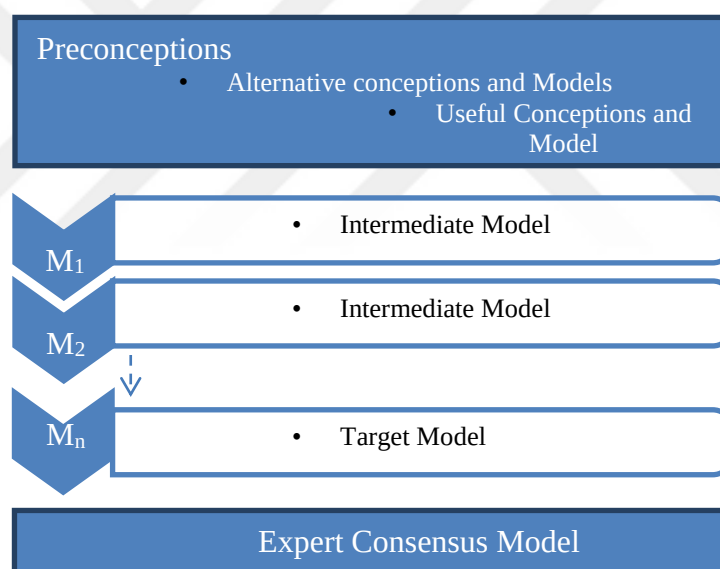


Figure 2.3: The framework for modern approaches to model construction (Clement, 2000)

The framework shows students' initial model (preconceptions) along with their reasoning prior to any formal instructions, intermediate models and reasoning development stage during the instruction, and finally a more scientific (target) model after completing the instruction. From preconceptions to target model or to expert consensus model, each step indicates students' cognitive development stages and model

alteration process, which provides instructors and curriculum developers a significant clue to organize a learning environment and curriculum (Clement, 2000).

2.4 Rationale for the Study

Quantum mechanics has become quite a popular subject within physical science education because of the acceleration in related scientific and technological developments (e.g., nanoscale science and engineering). However, many instructors have faced challenges in designing instruction and teaching quantum mechanics concepts because of the abstract nature of these concepts (Johnston et al., 1998; Zollman et al., 2002). Specifically, the different behaviors of subatomic level particles do not allow them to be perceived as macro-level objects that can be explained with Newtonian physics (Hurwitz, Abegg, & Graik, 1999; Ireson, 2000; Mashhadi & Woolnough, 1999; McKagan et al., 2008). Therefore, I examined students' learning of quantum mechanics in the context of a model-based approach to instruction, which I proposed would help students' sense-making process as they articulate initial models, reason through the use of these models, revise and reconstruct new models (Khan, 2007).

In examining students' learning of quantum mechanics concepts, I was not simply cataloging students' misconceptions or learning difficulties. Such studies have been done with a wide range of age groups, and, more or less, illuminate the quantum mechanics concepts with which students are most likely to struggle (Muller & Wiesner, 2002; Petri & Niedderer, 1998; Singh, 2001; Steinberg et al., 1999). In this research study, I have utilized this information to be able to develop a model-based learning environment, which I believe fostered model-based reasoning—an essential component in organizing foundational knowledge to analyze and interpret quantum phenomena.

2.5 Fundamental Quantum Concepts

Quantum mechanics content includes many essential discoveries that followed one another for the purpose of completion of the big picture. In this part, I will talk about the development process of fundamental concepts from different periods of early stage of quantum theory. I believe that these concepts illustrate a plausible map to understand the stages for the discovery of atomic models and electron's behavior.

2.5.1 Atom and Atomic Spectrum

When an atom and its components were under spotlight in the late 19th century, J.J Thompson, Earnest Rutherford, and Niels Bohr posed different atomic theories based on a combination of their observations of the conducted experiments as well as their everyday experience with classical mechanics phenomena. Each model seemed to be more adequate and desired to fill in the gaps that the previous ones had not. However, electron arrangement and atomic spectrum for multiple electrons was still a puzzle and could not be explained with the existing (classical) theories. Many later discoveries were the result of both successful and unsuccessful outcomes. In most cases, individuals dwelled on the doctrines of the existing theories, and that restrained them from making headway towards understanding the phenomena (Kuhn, 1970). Likewise, early atom theorists focused only on the problematic part of the current model and attempted to solve it within the borders of existing theories, since their experience with science and the real world did not allow them to think beyond that of classical mechanics borders. However, this vicious cycle became a snare and quantum theory came along with more “radical thinking” as Glaserfeld (2001) asserted.

Max Planck, who is referred to as the “father of quantum theory”, studied thermodynamics and blackbody radiation. He observed the different wavelengths emitted by a blackbody (as well as the energy distribution) and used classical mechanics to interpret his findings (Kuhn, 1978). However, to be able to fit the observations into his mathematical expressions, he had to exceed the limits of classical mechanics. He proposed the idea that was going to open the gates of a new approach to physics: energy emission could happen only with discrete values or quanta. In his work, Planck’s approach was rather innovative and his new way of thinking helped him to wriggle himself out of the traditional way of approaching phenomena, even though he was not sure of what he was doing at that time (Klein et al., 1979). In fact, his theory was not readily accepted by most physicists, including himself, (Montwill & Breslin, 2008; Zeilinger, 2000) until Einstein proved discrete energy packages for which he received the Nobel Prize. According to his own writing, indicated by Montwill and Breslin, (2008), Planck made an effort “to save physics from discontinuous energy levels”, but he was unable to achieve this (p.377). After his theory, Einstein being the first, physicists started to interpret the universe through different lenses. With that radical change, they started thinking about adopting non-traditional epistemological perspectives to read the laws of nature (Kalkanis, Hadzidaki, & Stavrou, 2003).

The Photoelectric effect experiment was established by Planck’s theory of quantization, which was initiated to extend the understanding of light. With this experiment, Einstein was able to determine the energy of each “photon” by using Planck’s constant. This experiment confirmed the particle feature of an electron after all the arguments about the nature of light and completed wave model which was proved

with double slit experiment (Young's experiment). Even though both experiments explain the electron nature, scientists adhered to one or the other since each experiment approached reality from a different perspective. Photons are considered as energy packages, but they can also be regarded as waves which have energy that spread out over a certain statistical area until they come across another particle.

Planck's discovery of the discrete energy model also inspired Bohr to announce his atomic model that also explains the color line on the atomic spectrum. As a follow up to Planck's quantized energy level model, he claimed that electrons orbit around the nucleus but can only exist in specific orbits. He also proposed that if an electron absorbs energy, it jumps to the next orbit and jumps back to the previous orbit by releasing radiation. The Bohr model is another theory that supports the particle nature of an electron asserted in Einstein's photoelectric experiments. However, there was still a disconnection between this model and the results of the double slit experiment (wave nature of electron). Therefore, even though this model was respected for a while, scientists did not stop questioning the structure of the atom or the electron's behavior. The studies to find out an electron's position in an atom were mostly continued with Schrödinger's wave equation and Bohr's statistical wave function.

3. METHODS

3.1 Introduction

The essential goal for this research was investigating students' conceptual changes when they were introduced to fundamental quantum mechanics concepts via a model-based learning module. With the model-based module, I tried to help students construct their own model of phenomena as part of the curriculum (Gobert & Buckley, 2000). To monitor students' conceptual changes, I sought to see how students use physical, virtual, graphical, verbal or mathematical models to make meanings about the quantum phenomena and how they represent their internal model to explain what they know. Therefore, mixed methods was chosen as a research method for this study. Mixed methods research included both qualitative and quantitative data analysis to answer research questions, and it requires both qualitative and quantitative data collection and analysis (Creswell, 2013). Qualitative inquiry has widespread used, is very informative, and a valid research approach (Avison et al., 1999; Carroll & Swatman, 2000; Markus, 1997), that provides for deeper understanding of explicit patterns, examples, or structures from the targeted population (Denzin & Lincoln, 1994, 2005). Quantitative research, on the other hand, strictly controls the variables and allows running statistical analysis to test any hypothesis (Creswell, 2009).

To achieve the research objectives, it is crucial to determine the methodological framework, the sequence of research methods (e.g. case study, action research, phenomenography, phenomenology, field studies, etc.), and analysis treatment of the data. In next section, I will discuss the methodological perspective, data analysis process,

research design where research strategy, instruments, profile of participants, data collection, and data analysis processes are explained and finally present the instructional material's design and introduce the model-based learning module.

3.2 Methodological Perspective

A methodological perspective provides researchers the opportunity to manage and analyze the data (Ritchie, et al., 2013). According to Creswell (2007), there are five philosophical assumptions that need to be considered before starting a research process. Those are: the nature of being/reality (ontology), theory of knowledge (epistemology), the nature of research procedure (methodology), the study of value (axiology), and the way of expressing their research (rhetorical). To cover these assumptions, different interpretive paradigms such as constructivism, and positivism could be preferred by the researcher (Denzin & Lincoln, 2005). Constructivism is chosen as the research paradigm for this study. Based on the constructivist' paradigm, the "truth" is a relative notion which may differ from individual to individual depending on one's interpretation. Therefore, it is very important to obtain students' subjective interpretations of their experiences in the world. The Constructivist paradigm provides researchers all necessary communication tools (Crabtree & Miller, 1999). Combinations of subjective interpretation with existing knowledge result in internal representation of each phenomenon (Bednar et al., 1992; Halford, 1993), which are considered fundamental pieces of understanding the external world (Craik, 1943). Hence, investigating individuals' internal representation of any piece of knowledge via their external representation provides us better understanding of the learning process and possible teaching/ learning environments. Many researchers agree that this case study is quite a

useful method for finding out human behavior since it allows a researcher to investigate any single subject's case in depth (Stake, 1978). Case studies may include single or multiple cases as well as various types of analysis (Yin, 1984). Yin (2003) propounded that research may prefer to use case studies when 1) the research is trying to find out the answer of how and why questions; 2) researcher(s) thinks the whole contextual setting is significantly contributing to understand the research phenomena. Therefore, it is important to investigate the system as a whole; 3) there is no clear distinction between researched subjects and the setting; and 4) there is no possible way for external manipulation to the research subjects' behavior. Since this study aimed to investigate each student's model alteration process in his/her own learning context, I used multiple case studies to understand the model change process as well as the reasons behind it.

3.3 Research Design

3.3.1 Context of the Study

The research study was conducted in three phases. The first phase focused on the students' ideas and initial models about atomic structure, energy levels, and atomic spectrum and asked them to draw a concept map of those three concepts. The second phase encompassed the instruction of relevant concepts. Specifically, one group of students (the intervention group) received a model-based learning module (MBLM), which consists of computer-based simulations, hands-on activities, and a booklet that is compiled of all relevant concepts in sequence. A second group of students (the control group) received the same booklet, all the computer-based simulations, and the assessments in exactly the same order as the MBLM group. In this phase, I collected students' worksheets that consist of drawings, observational entries, written explanations

and mathematical calculations, assessment responses from both the intervention and control group. The third phase consisted of post-intervention data collection in which I conducted a post-interview with the students and asked them to draw a second concept map of the same concepts for which they drew a concept map in phase I. Finally, in the fourth phase, I qualitatively and quantitatively analyzed the data from the intervention group and the control group to interpret students' improvement in their understanding of foundational quantum mechanics concepts.

The duration of the study was 10 meetings, each lasting up to 60 minutes (two interviews and eight instruction sections). During Phase II and Phase III, students were video and audio recorded while they were interacting with learning materials. In addition, students were requested to fill out an exit questionnaire (see Appendix E) after each lesson to share their perceptions about that specific lesson, activities and learning materials.

3.3.2 Participants and Context

The Participants in this study were freshman and sophomore level physics and engineering students who were enrolled in PHYS 272 and in PHYS 272H (Electric and Magnetic Interactions) at Purdue University during the spring semester of 2016. PHYS 27200 and PHYS 272000H are taken by most of the physics and engineering undergraduate students and focuses on concepts of electric and magnetic fields and an atomic description of matter to describe polarization, fields produced by charge distributions, potential, electrical circuits, magnetic forces, induction, and related topics, leading to Maxwell's equations and electromagnetic radiation and an introduction to waves and interference. PHYS27200 students have taken as a prerequisite course PHYS

17200 (Modern Mechanics), which is an introductory calculus-based physics course that includes Newtonian mechanics, conservation laws, energy quantization, entropy, the kinetic theory of gases, and related topics in mechanics and thermodynamics. Therefore, it is most likely that participants in this study had encountered concepts related to energy quantization, energy levels, and atomic spectrum prior to this study.

All participants were selected based on an initial screening process (see Appendix A) in which they provided information about their background in modern physics, particularly regarding atomic structure, energy levels, and atomic spectrum. I eliminated the participants who had any substantive prior knowledge of quantum mechanics. After the selection process, I contacted students who were selected as participants to schedule pre-interview meetings and instructions. The number of participants for this study was 8, half of the students for the intervention group and half of them for the control group. Due to the qualitative part of the study, I expected to receive a large amount of data from each student. To this extent, I limited the number of participants to increase the detailed analysis of data. With that information, I was also aware the fact that the quantitative analysis could not be generalized. However, I believed it gave me a good statistical evidence to support my qualitative analysis and overall performance between two particular groups of students.

3.4 Designing Learning Materials

Learning materials utilized in this dissertation study was developed after a pilot study which inform me about undergraduate physics and engineering students existing models about fundamental quantum mechanics concepts such as Atomic structure, energy levels and atomic spectra. I used a small (five questions with two or three sub-questions

in each) open-ended questionnaire to reveal students representational and verbal models. The details about developing interview questions for pilot and large study is presented in section 3.4.1. In total 11 students volunteered to participate the questionnaire. Students were initially given 20 minutes to think alone and answer the questions. After completion of 20 minutes, I asked them to explain and elaborate their answers as part of think aloud process. Think aloud part of the interview provided me clearer and more detail look in students' models and helped me understand what they really mean or how they reason about any particular quantum concept. Analysis of the pilot study informed the design of instructional materials (Model-based learning module) to be used for the larger study.

Learning quantum mechanics is considerably difficult for many individuals. Therefore, research on undergraduate students' quantum mechanics learning is gradually growing in the physics education research (PER) community (Fischler & Lichtfeldt, 1992; Singh, et al., 2006). Studies to examine students' misconceptions and learning difficulties indicate that high school and college students still have a hard time making sense of many of the quantum mechanics concepts after they successfully completed course work (Akarsu et al., 2011; Griffiths & Preston 1992; Ireson, 2000; Rebello & Zollman, 1999, 1992; Styer, 1995). The results of these studies have motivated the PER community to take action to develop new and more innovative instructional designs to address learning difficulties while actively engaging students in the learning process.

One popular instructional method that encourages active involvement and critical thinking in science education is inquiry-based teaching. According to reports published by National Research Council [NRC] (1996) and Next Generation Science Standards (NGSS), students in K-12 science classrooms benefit scientific inquiries to construct

knowledge based on claims and evidence. Science teachers design their curriculum integrated inquiry-based learning to meet with science standards and specific science learning goals and overcome students' learning challenges in some science concepts (Khan, 2007). In the inquiry-based learning environment, students are expected to develop an explanation of real life phenomena after engaging in scientific investigations (Edelson, Gordin & Pea, 1999). Additionally, an inquiry-based learning environment offers learners a well-organized way to question, test, refine, and understand a scientific situation. However, it seems that many teachers do not have a clear picture of how science should be taught and what inquiry-based teaching looks like in schools (Crawford, 2007; Passmore et al., 2009).

Researchers have made extensive efforts to analyze students' conceptual understanding and have tried to develop new methodologies to improve the quality of learning. From that perspective, a body of the research claims that students' conceptual models can play a very essential role in students' conceptual understanding (Clement, 2000). Therefore, model-based research has been advocated as an instructional method in which learners have an opportunity to use and/or build models and be active in their learning (Khan, 2007; Nersessian, 1999).

3.4.1 Designing the Interview Questions

There is not a commonly accepted instrument to determine students' conceptual and procedural understanding of quantum mechanics (Rebello & Zollman, 1999). Therefore, I developed interview questions to ascertain students' initial understanding of the hydrogen atom, energy levels, and the emission/absorption of photons. To design the interview questions, I first developed a concept map (see Figure 3.1) of what I considered

to be the main quantum concepts by investigating over more than ten high school and college level textbooks. This map helped determine critical and key concepts that have connections with both the early stages of atomic models and more sophisticated quantum phenomena. I reviewed the concept map with a physicist to ensure accuracy. As a result of this analysis, it was apparent that understanding energy levels and atomic spectra was fundamental to building knowledge of quantum mechanics. I used Shavelson's framework (Shavelson et al., 2003) to design questions according to four kinds of knowledge: declarative, procedural, schematic, and strategic (See Figure 3.2). Some questions have multiple parts that requiring descriptive, procedural, and schematic knowledge. For those parts, students should be able to define, use their problem-solving skills, and sketch a model to represent their reasoning.

After a discussion with experts in physics and curriculum & instruction, I conducted a major revision to the questions for the main phase of the study. This time I examined the students' responses from phase 1, and tried to discard any question that caused misunderstanding and added more questions to grasp a more detailed outcome. After the first draft revision was completed, I asked an expert physicist to review questions for accuracy and coherency. Based on his comments, I and two other committee members (both are professors in physics and both of them conducting physics education research) met again to complete a final revision. All questions are aligned with MBLM and the activities (see Appendix B).

Knowledge Claim	Content	Learning Objective	Assessment
Declarative	Knowing that--facts and concepts in the domain	<i>Identify and describe</i> particles which comprise atoms	Define, list, state, label, name, describe
Procedural	Routine procedures and some aspects of problem solving	<i>Describe</i> the relationship between atomic spectra and the electronic structure of atoms	Describe, summarize, interpret, illustrate
Schematic	Conceptual models of how the natural world works	<i>Explain</i> qualitatively the origin of emission or absorption spectra of gases	Predict, explain, synthesize, infer, integrate
Strategic	Knowing when, where and how knowledge applies	(higher level problem solving and knowledge transfer)	Reasoning, conceptualize, apply knowledge, pose question

Figure 3.2: Shavelson's framework

3.4.2 Designing a Model-Based Learning Modules

The curriculum that I designed for this study marries the affordances of inquiry-based instruction and model-based instruction. Specifically, I developed a model-based inquiry curriculum that engages learners in scientific inquiry and is focused on the creation, evaluation, and revision of scientific models that can be applied to explain and predict the natural world (Schwarz, 2009). Students in the intervention group of the study developed and revised their models of the atom, energy levels, and atomic spectra throughout the lessons and used these models to explain more complex phenomena. Model-based inquiry instruction involves dynamic process of iteratively revising models to be consistent with theory and evidence, and models that can be used to predict and explain multiple phenomena in the natural world.

This study was grounded in a view that learners construct their knowledge and develop models to represent their understanding as they share and communicate with others (Buckley, 2000; Gentner & Stevens 1983; Johnson-Laird, 1983). A model-based

framework for this project resonated with more contemporary views of science learning as a process of domain-specific construction of knowledge (Carey & Spelke, 1994; Gelman & Brenneman, 2004).

Cognitive researchers have proposed that individuals develop models to help make sense of and explain the phenomena around them (Gentner & Stevens 1983; Johnson-Laird, 1983; Larkin & Simon 1987; Pirnay-Dummer et al., 2012). Giere (2004) suggests that domain knowledge (in this case, science knowledge and more specifically quantum mechanics knowledge) is organized in terms of families of models representing salient features and relationships of things or phenomena in the world. Therefore, models are important conceptual tools that allow people to predict, organize, explain, describe, communicate—the very essence of engaging in science inquiry.

The main goal for the research was to develop a model-based learning module (MBLM) (See Appendix C) to support student development in understanding and evolution of reasoning. To accomplish this goal, I used different form of models to address different perspectives of fundamental quantum mechanics concepts. Since use of models has some limitations in terms of representing the real object/phenomena, I tried to include more than one model-based inquiry activities per lesson. In addition, to prevent further possible misconceptions, students will be encouraged to think about the benefits and drawbacks of the particular models after every activity.

The Model-based Learning module has four units and each unit includes one or two lessons. Each lesson starts with learning objectives and common student misconceptions, which are aligned with model-based activities. Questions or guidance in the activities were purposefully emphasized to address the key points, which we think

trigger some misconceptions. In the introduction section, there are a couple core questions about each topic covered in the related lesson. Those questions are targeted to reveal students' predictions before making any observations. The last section in MBLM is called *model based reasoning* and discusses what reasoning skills students are expected to develop and how they should be able to represent their understanding.

The model-based activities were supported with computer-based simulations which were developed by different groups such as University of Colorado (PhET simulations), Kansas State University (Hydrogen spectroscopy), Astronomy education at the University of Nebraska-Lincoln (Hydrogen Atom Simulator), etc. and the physical models which developed by me or adopted from other studies. Below, I gave a description of each models based activities and provided information about design process including design principles and my rational for choosing specific models/simulations. All model-based inquiry activities were developed to complement each other in a way that students have opportunity to engaged with different models and understand the perspective that they bring in. With physical models students manipulated phenomena physically by receiving tactile feedback. Computer-based simulations, on the other hand, gave another perspective to students which helps them to visualize some sub-atomic phenomena.

Early Atom Models

The first unit of MBLM is called Structure of Atom and consists of two lessons. Current research conducted to reveal students' misconceptions about atomic structure showed that planetary orbit idea is resistance to change for most students and they perceive electron as negatively charged tiny balls move around the nucleus. Therefore, in

this unit, all the MBLM activities were addressed to help students overcome their misconceptions by simulating the early scientists' experiments to understand atomic structure.

In the first lesson, there are five model-based inquiry activities to investigate two early atomic theories: Thomson and Rutherford atomic models. Each atomic theory is simulated both physical and computer-based simulations (see Figure 3.3).

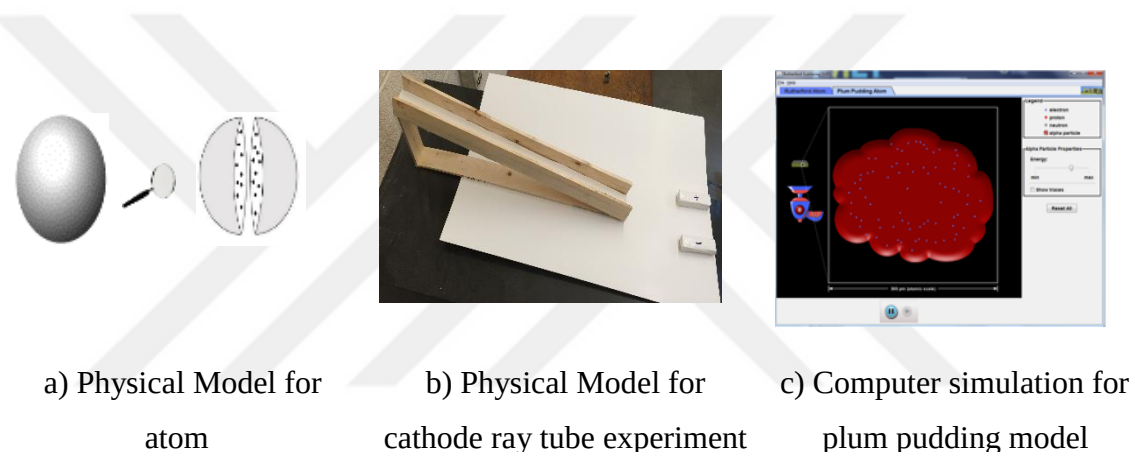
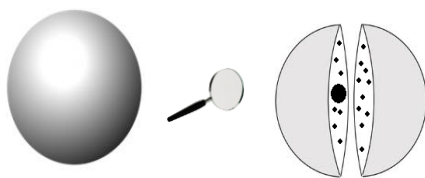


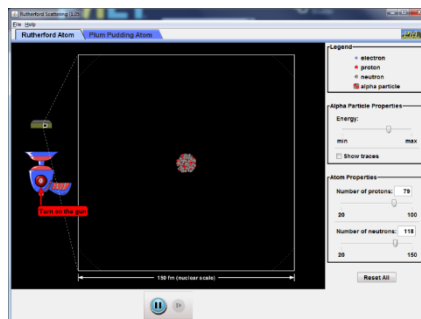
Figure 3.3: MBLM atomic structure activities (Thomson Models)

Figure 3.3a shows the physical atom model was developed by me and it simulates Thomson's plum pudding model. This model aimed to simulate the conditions when J.J. Thomson initially tried to understand what an atom was made out of. The spherical foam ball represents an atom which was a mystery for physicists in early 20th century. To imitate photons sent to atom, students used skewers to discover what is inside an atom. With this model, students were expected to discover small particles located on random places inside the ball by using the skewers. The second model-based activity was another physical model that simulates electron cathode ray tube experiment which also was developed by me. The model was designed to demonstrate how J. J. Thomson set up his

experiment to find out electron's properties and especially its charge. In the model-based inquiry activity, students received a wooden ramp and small magnetic beads that represents electrons. Two magnets covered with labels that showed positive and negative charges were placed at the bottom of the ramp. The task for each student was that identifying the attributions the "electrons" by rolling them one by one from the top of the ramp and observing direction of small beads. With this inquiry activity, students were able to describe electrons' charge similar to what Thomson observed in the cathode ray tube where electron beams deviated by anode. The discussions at the end of the activities guided students to make connections between this activity and cathode ray tube experiment. This connection was very important because students needed to conceptualize the reasoning behind the actual experiment setup. The third model-based inquiry activity for Thomson model was a computer-based simulation developed by University of Colorado Border. Students engaged with the PhET simulation –models of the hydrogen atom/ Plum Pudding Atom. This simulation aimed to deliver the same idea with the first physical model which reflected an effort to understand what is inside an atom. The visual aspect of this simulation provided students with insight that might be difficult to attain from physical model. After completing the simulation, students were exposed all different models and conceptualized the Thomson model by mimicking his scientific pathway.



a) Physical Model for atom



b) Computer simulation for alpha scattering experiment

Figure 3.4: MBLM atomic structure activities (Rutherford Models)

The second set of model-based inquiry activities addressed the Rutherford atom model. For the Rutherford model, students were given a similar foam ball and skewers, but this time a big (massive) bead was placed at the center of the ball (see Figure 3.4a). The purpose of using this physical model was to simulate the gold foil experiment that Rutherford and his colleagues conducted as part of their radioactivity studies. This activity intended to help them understand the discovery of nucleus. In that context, students tried to identify what was inside an atom by using the skewers. After the physical model, another computer simulation ((PhET –models of the hydrogen atom/ Rutherford Atom) was embedded in a model-based inquiry activity to simulate Rutherford's gold foil experiment (see Figure 3.4b). Students started observation of alpha particles trajectory with Thomson model in mind. After they recorded their observational notes, they started discussing if Thomson's atom model was accurate and what they observed. Expectantly, they came up with the idea of nucleus at the center, positively charged and very massive. Additionally, completion of these two model-based inquiry about Rutherford models gave them insights about how early scientists discovered the

components of atoms although they did not design their experimental settings accordingly.

The next lesson consisted of two model-based activities to discover planetary model. Students initially observed electrons' spiral motion around a nucleus via another PhET simulation called Models of the Hydrogen Atom – Classical Solar System (see Figure 3.5). This simulation provided only an animated version of an electron's motion if it would circle around a nucleus with regard to classical mechanics. The reason that this animated visual model was included in the model-based activity was to give students an idea what would an electron's spiral motion look like. After observing the visual model, students calculated the motion of electron by using centripetal and Coulomb force equations. Both visual and mathematical models aimed to support students' conceptual understanding of why planetary model did not predict atomic structure accurately.

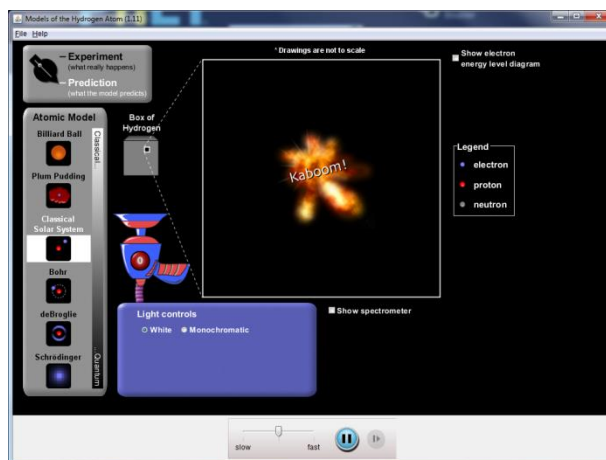
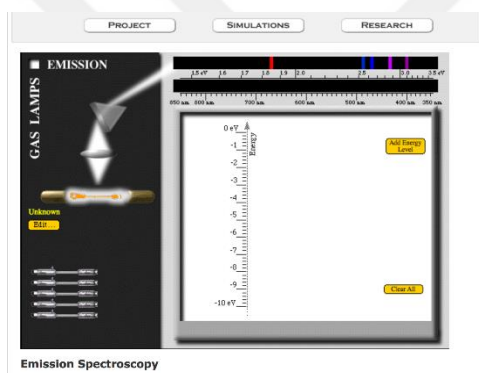


Figure 3.5: MBLM atomic structure activities (planetary models)

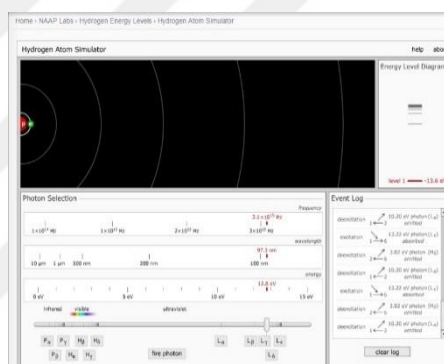
Atomic Line Spectra & Energy Levels

The second MBLM unit was delineated to introduce Atomic spectra. The first lesson of the unit focused on energy quantization. Current studies showed that students

have some non-normative ideas such as energy of an atom can take any value, electronic transition lines are equal to spectral lines (Akarsu, 2000; Rebello & Zollman, 1999). Therefore, all model-based inquiry activities were designed to revised students' non-normative models/ideas. After students discussed about what quantization, ground and excited state mean, they played with energy levels and observed electronic transitions via hydrogen spectroscopy simulations developed by PER group in Kansas State University (see Figure 3.6a).



a) Computer simulation for hydrogen spectroscopy



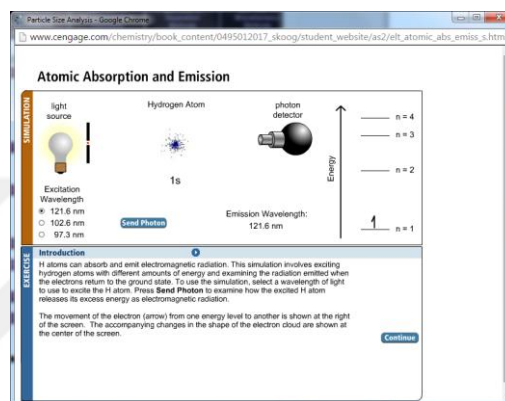
b) Hydrogen atom computer simulation

Figure 3.6: MBLM energy quantization activities

The main purpose of this model-based inquiry activity was to indicate the relation between energy levels, electron transitions and spectral lines. The following MBLM activity was also computer simulation called *Energy levels and Photon absorption of Hydrogen atom* developed by astronomy education group at the University of Nebraska (see Figure 3.6b). This visual model helped students to understand the relation between frequency/ wavelength and energy of emitted photon. As part of this activity, they also used mathematical models to calculate energy at the first five energy levels and compared their results with the one shown in the simulation. The lesson was concluded by

discussing the spectral line series such as Lyman, Balmer, and Paschen series.

Unfortunately, I could not find a well-fitted physical or visual model for the spectral line series due to the nature of the concepts. However, students were introduced the equations for each line series and guided to calculate first three wavelengths for each series.



a) Hands-on model for atomic spectroscopy b) Computer simulation for absorption and emission phenomena

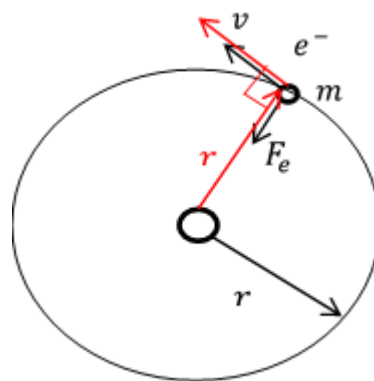
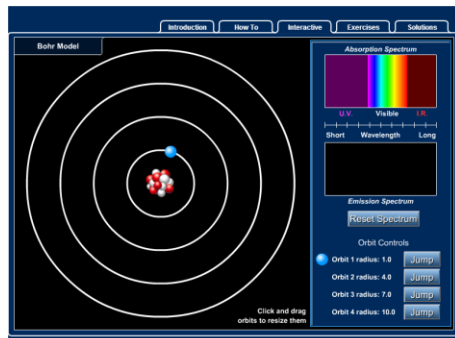
Figure 3.7: MBLM atomic spectra activities

The next lesson in the second unit is called Atomic Line Spectra & Energy Levels. The model-based inquiry activities of this lesson were a physical model which mediated students to the conceptual idea about every element has a unique spectral lines (see Figure 3.7a) and a visual model which helped students to investigate absorption and emission process via computer simulation (see Figure 3.7b). In the first model-based activity which was adopted from Hydrogen Spectrum Activity and retrieved from <http://www.carolina.com/teacher-resources/Interactive/hydrogen-spectrum-activity/tr10770.tr>, students were given a spectroscope, spectrum tube power supply and different gas spectrum tubes. Via spectroscope, students observed spectral lines for each

gas and record the wavelengths for specific spectra. Eventually, students realized that spectra of different elements were not identical. Like a fingerprints, spectral lines allow us to identify elements. The next model-based activity involved another computer based simulation called Atomic Absorption and Emission developed by Cengage Learning. This simulation is designed as interactive tutorials and embedded some introductions and questions throughout the engagement. With this simulation, students observed atom(s) when it was hit by a photon. As a result, students found out atom takes different shapes when it collided with a photon of different wavelengths.

Both model-based activities in this lesson aimed to help students making transition between energy levels and atomic spectra.

Bohr Model



a) Computer simulation for Bohr radius

b) Graphical model for Bohr radii
formula derivation

Figure 3.8: MBLM Bohr model activities

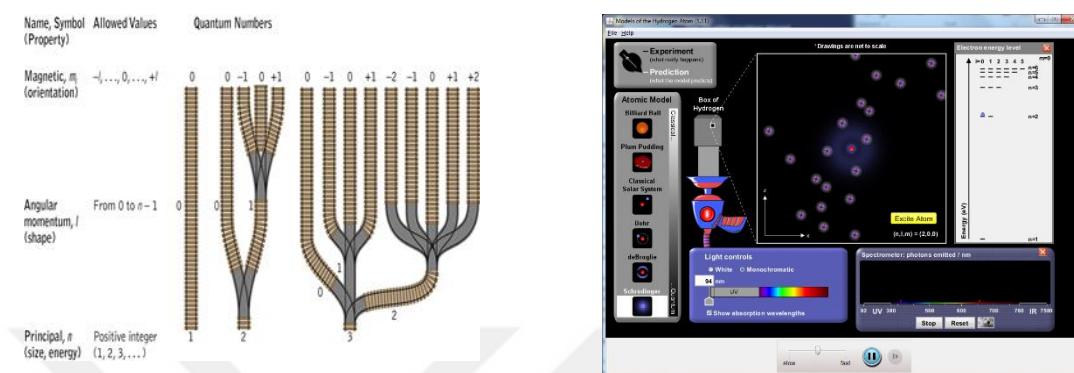
The third MBLM unit addressed the Bohr's model of the atom. Prior studies argued that many post-secondary and first-year undergraduate students have a Bohr

model in their mind as atomic structure. The only lesson in this unit included two model-based activities (see Figure 3.8) which intended to introduce the Bohr model and Bohr's assumptions which were based on classical and quantum mechanics. Knowing the reasoning behind Bohr's theory gave students a perspective to distinguish what the Bohr atom model explained and what it failed to explain. The first model-based activity involved computer based simulation called *Bohr Model* developed by McGraw Hill Education. The simulation allowed observing emission spectra by manipulating Bohr's radii (see Figure 3.8a). To complement this simulation, students were guided to derive Bohr radii formula departing from Bohr's assumptions and classical mechanics equations in the second model-based activity. Once they derived the formula, they had a chance to confirm their mathematical models of Bohr radii with what they observed in the simulation. The following model-based activity consisted of another physical manipulative which designed by me to introduce the potential energy of electron on different energy levels. The model basically contained magnets which were placed on different levels in a sealed black box. Another magnet was attached on the tip of a tongue depressor. By bringing the tongue depressor near to the box, students experienced the strength of interaction between magnets on different levels and figured out the relationship between electrons potential energy and its distance from the nucleus.

Quantum Numbers

The fourth MBLM unit introduced wave mechanics (quantum mechanical atom model) that consisted of three lessons. Common learning difficulties about quantum numbers indicated that students do not have a complete understanding about s, p, d, f orbitals (Zoller, 1990), and they did not know terms such as orbital and wave function

(Bethge & Niedderer, 1996; Petri & Niedderer, 1998;). In the first lesson, model-based inquiry activities focused on quantum mechanical hydrogen atom structure.



a) Visual model for four quantum numbers b) Computer simulation for de Broglie and Schrodinger atom models

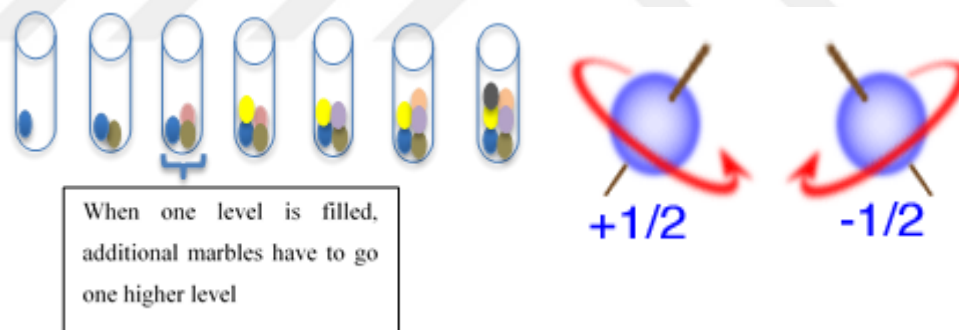
Figure 3.9: MBLM quantum mechanical hydrogen atom

The first model-based activity involved a graphical model and helped students visually see the relationship among four quantum numbers (see Figure 3.9a). For the students who struggle to memorize how orbital quantum number, and magnetic quantum number can be calculated for any given principal quantum numbers took advantage of the graphical representation to construct a meaningful model of quantum numbers. In the following model-based inquiry activity, students engaged with two PhET simulations to investigate de Broglie and Schrodinger atom models (see Figure 3.9b). As part of the activity, students were required to make a prediction before engaging with the simulations and then they recorded their observations. Later, they were asked to explain their reasoning to compare their observations and predictions about these two quantum mechanical hydrogen models. With this activity, I aimed to help students make the transition between the early atomic models and quantum mechanical atomic models. In the third activity of this lesson, students derived time- dependent Schrödinger equation

for one spatial dimension by using basic knowledge of such phenomena as non-relativistic kinetic energy, de Broglie's wave equation, and wave function. The purpose of this activity was to point out scientist way of transitions from classical mechanics to quantum mechanics.

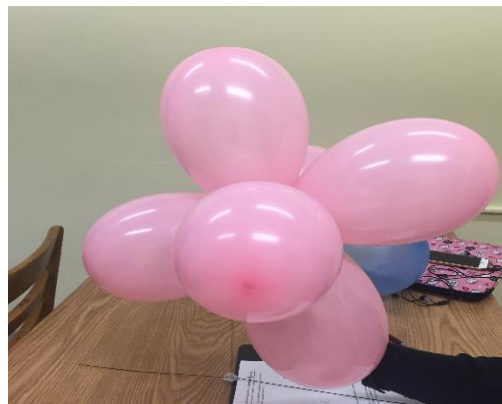
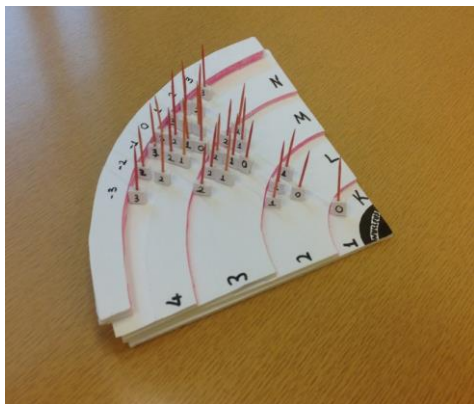
Multi-Electron Atoms

The second lesson was designed to study electrons' arrangement in an atom. Therefore, all model-based inquiry activities served for the purpose of delivering the conceptual understanding of necessary rules and principles to help us configure electrons based on quantum numbers which seemed to be very challenging for students (Zengin et al., 2009).



a) Physical model for Pauli principle

b) Physical model for electron spin (up & down)



c) Physical model for electron configuration and orbital notation

d) Physical model for orbital shapes

Figure 3.10: MBLM multi-electron atom activities

The first model-based activity in this lesson is a physical model to show Pauli principle and adopted from Walker (2010)'s textbook. Figure 3.10a shows the physical model for Pauli principle where seven tubes represent energy levels and small marbles represent electrons. Students started placing one marble at a time to each tube. When they finished placing the first marbles in each tubes they went for the second round by skipping the first tube. After the second round, students placed the third marbles in the tubes by starting from the third tube. However, this time they saw that third marble did not go to the bottom of the tube since there was not enough room at the bottom. Therefore, marbles started filling the second level. The purpose of this physical model was to convey the idea that the Pauli exclusion principle asserted about neither of the two electrons can share the same quantum number. Similarly, the second model-based inquiry activity was designed to reinforce the electron configuration and principles including Aufbau and Hund's rule. The physical model, which was adopted from Choda & Chenprakhon (2015), provided a good demonstration/manipulation for shells, sub-shells,

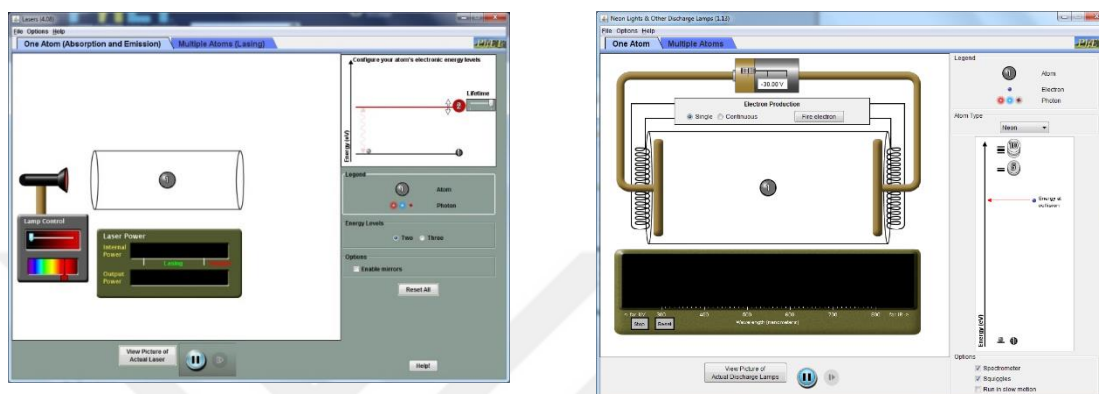
and magnetic quantum numbers (see Figure 3.10c). By placing different color beads on toothpicks which represent unique quantum states in an atom, students constructed a meaningful understanding about electron arrangement for multi-electron atoms. The following model-based inquiry activity includes a physical model developed by me and aimed to illustrate the concept of electron spins (up & down) (see Figure 3.10b).

Although this model –based inquiry activity did not require any measurement, it was important in terms of showing a tangible representation for very abstract and challenging spin concept to students. With this activity, students visually observed and played with two spin-up and spin-down electrons and connect that to their angular momentum which they already became familiar when they learned quantum numbers. The last model-based inquiry activity in the unit focused on introducing orbital, shell and subshell ideas as well as their shapes. After students constructed their conceptual understanding of quantum numbers, electron spin and how to arrange electrons in atoms, they started using their models to represent orbital shapes by using balloons in the final model-based inquiry activity which was already used as teaching tool and mostly for demonstration purposes by many educators. In the MBLM activity, students used balloons to create their models of s and p orbitals without any prior demonstration or guidance. Figure 3.10d presents a Student M3's model of p-orbitals.

Application

The last unit was devoted to the application of energy quantization, electronic transitions and atomic spectra in daily life. This lesson was especially significant since the most students did not think that the effect of quantum mechanics is not easily seen in daily life (Bethge & Niedderer, 1996). With two computer-based simulations, I aimed to

reinforce students' understanding about the mechanism derived from quantum phenomena via laser and neon lights concepts which are part of everyday experiences.



a) Computer simulation for one atom and multi-atom Lasing

b) Computer simulation for Neon Lights & Other Discharge Lamps

Figure 3.11: MBLM atomic spectra applications activities

Figure 3.11a shows a screenshot of PhET computer simulation for Laser. Students engaged with the “one atom” and “multi atom” options to observe different intensity of absorbed/emitted photons. By changing some variables such as light intensity, mirror reflectivity, energy level distance and lifetime, they tried to obtain optimum lasing. The next model-based inquiry activity, similarly, imitated neon discharge lamps (see Figure 3.11b). Students used the same conceptual knowledge to understand the working mechanism. Overall, Laser and Neon light / discharge lamp activities provided a good exercise to students to be able to make the connection between what they have learned and how these quantum phenomena are applied in real life technology.

3.5 Data Collection

Initially, I conducted a pre-interview (see Appendix B) with all the participants to determine their initial understanding of fundamental quantum mechanics concepts. The interview consisted of two main components: think-alone and think-aloud. During the think-alone process, participants solved 10 questions within 20 min. The questions were mainly descriptive and schematic; therefore, I gave participants time to think alone to prevent an “inhibitory effect” created by the researcher (Rotter & Portugal, 1969, pg. 338). After they completed the questions, I asked them to explain their responses (think-aloud) with more detail and asked questions to probe their thinking and sense-making process.

Based on the result of the pre-interview, participants were assigned to one of two groups: treatment (MBLM) and control (TCBS). Since students participated to this study as volunteers and in their free time, the groups’ working times were arranged based on each student’s schedule. In fact, even all MBLM or all control group students were instructed at the same day or time. However, to be able to keep records of students’ discussions while they were working on activities in pairs, I tried to arrange at least two students in one instructional group in both MBLM and TCBS groups. All instructional activities were conducted in the department of physics and astronomy. Students were requested to bring their own laptops to the instructional sections. If any student informed us that s/he did not have a laptop or was not able to bring her/his own computer, then I provided them a laptop to work on. All other instructional materials were provided to each student or group.

Students in the treatment group received a model-based learning module (MBLM), which includes a series of lessons that incorporate modeling-based activities, computer-based simulations, on-line discussions, and embedded assessments to encourage them to articulate/improve their model-based reasoning and critical thinking, as well as a booklet that consists of a collection of relevant chapters about the quantum mechanics topics in sequence (See section 3.4.2 for more detail about MBLM activities). They were also provided with worksheets (see Appendix C) for each activity to enter their observational and interpretational records. Additionally, each student took assessments (see Appendix D1-D6) between lessons. MBLM students were asked to record their prediction and then observation on their worksheet before and after the model-based inquiry activities. In this way, they had a chance to compare their initial models with the final models which they refined and revised based on their engagement with physical, graphical, mathematical or visual models. They also encouraged to discuss their observations with their pairs after some of the model-based activities. Although model activities (particularly simulations) were individually completed, some of the activities (e.g. electron configuration physical model) required a collaborative work with their pairs. During their collaboration, they were encouraged to talk to each other and answer their possible questions instead of the researcher.

The control group received the same booklet, all the computer-based simulations, on-line discussions, worksheets for each activity (see Appendix F), and the embedded assessments exactly in the same order as the MBLM.

The total time for the study was four weeks. All groups took the same amount of time to complete their tasks. The pace of the activities was pre-estimated and the timeline

was already determined by me. However, if students could not complete the activities during the pre-determined timeline, then they were given extra time to finish the activity. The same amount of time was given to the control group for the same lesson as well to maintain consistency.

I presented during the instructional time for each group of students by giving the necessary initial instruction for each lesson and each activity. However, my role for the treatment group were slightly different from that of the control group. During intervention, I was answering students' questions by guiding them through using their model based reasoning. Furthermore, I tried to refer the model-based inquiry activities and the ultimate message delivered through engagement with different models. For control group, on the other hand, I answered students' questions by guiding them to find the correct answer (please see section 3.8 Role of Researcher for more details). The instructions were videotaped and audio recorded. I also collected each individual's online discussion entries, assessment responses, and worksheets.

3.6 Data Analysis

Interview data and video/ audio records during students' engagement with MBLM were transcribed and analyzed using constant comparative methods of analysis (Glaser & Strauss, 1965). Constant comparative method is a process in which the researcher examines any qualitative data by seeking the similarities or differences with other parts of the data to map the relationships between all parts of the data (Thorne, 2000). I looked for patterns in students' responses indicating normative and non-normative ideas. I created a rubric of models for each question to facilitate analysis. The rubric for models was constructed and organized from entity level (classical perspective dominant) to target

model (appropriate quantum mechanical perspective dominant). For descriptive questions I sought key words and scientific jargons. For schematic questions, I looked for evidence of the appropriate representation and accuracy in drawings. If a student had all of the appropriate words, formula, and drawings, s/he was categorized in targeted model level. I then categorized students' most normative and non-normative responses/explanations to determine patterns that characterized their understandings.

Students' drawings were scored according to the model-based rubric that I developed based on scientific accuracy of the models. Similarly, students' worksheets and inter-lesson assessment responses were analyzed with these methods. The coded names were represented the initial of MBLM or TCBS for the individuals who will attend one of the instructional settings.

3.7 Mapping the Presentation of Findings

There are three main purposes of this study. These are: 1) to investigate first-year physics and engineering students' pre-instruction conceptual models of atomic structure, energy levels, and atomic spectra; 2) to monitor the evolution of students' models over the course of their model-based instruction learning experiences; 3) to compare the evolution of students' models between those who received the model-based learning instruction and those who experienced traditional computer simulation instruction. In following three chapters, I describe the findings that are related to these three goals.

First, in Chapter 4, I present students' pre-instruction understandings and reasoning of atomic structure, electron's attribution, energy levels and atomic spectra. Students' initial models and the reasoning provide significant information about their

prior knowledge of quantum mechanics concepts and how students conceptualized ideas that they have learned in courses prior to this study. Furthermore, analyzing students' answers across the pre-questionnaire questions may provide insight into why students fall into a classic mechanics-dominant model.

Second, in Chapter 5, I examine transitions in students' model development and elaborate on the pattern(s) that individuals followed in both model-based and traditional computer-based learning groups. In chapter 5, each MBLM students model evolution process will be monitored across each model-based inquiry entries on worksheet, assessment answers and pre-posttest responses for every quantum mechanics concept. In this chapter, I will present each cases separately.

Finally, in Chapter 6, I present an analysis of students' models vis-a-vis the target model—i.e., a quantum mechanical model. I also sought the information which type of instructional methods (MBLM or TCBS) helped students who started with different quantum mechanics model better to shift their models more targeted level. As model-based learning module (MBLM) encouraged students to take a more sophisticated and expert-like approach, I expected that students in the MBLM group represented their models of atoms, energy levels, and atomic structure in a way that is closer to the target model, and that their explanations and terminology will be more scientifically appropriate when compared with the students who were in the traditional computer-based simulation (TCBS) group. In chapter 6, overall students' performance in two different conditions was statistically analyzed. I first looked the amount of improvement of both MBLM and TCBS students' models from pre-test to post-test. Second, I examined the model change rate among MBLM students in compare to TCBS students. Finally, I identified what were

the patterns for model transitions in each condition. In another word, how likely entity level models were improved toward targeted models by using either way of instructional methods.

3.8 Role of the Researcher

The researcher's role in qualitative research is very different compared to his/her role in quantitative research. While participants are mostly expected to behave independent from the researcher in quantitative study, participants may have a closer relationship with the researcher in qualitative research. Maykut and Morehouse (1994) stated that "The qualitative researcher's perspective is perhaps a paradoxical one: it is to be acutely tuned-in to the experiences and meaning systems of others—to indwell— and at the same time to be aware of how one's own biases and preconceptions may be influencing what one is trying to understand." (p. 123)

As a novice researcher, I have been working on this project for three years. During these years, I conducted a deep literature review in both pedagogy and the science content. Through the experience of conducting a review of relevant literature in addition to the courses that I have taken as part of my PhD program, I have gained a broad expertise for conducting the current project, specifically for designing the model-based learning module, developing interview and assessment questions, and designing this study on students' quantum mechanics conceptions. Throughout the study, I was the only researcher to communicate with students, including conducting all of the interviews, facilitating students' progress during the interventions. In many qualitative studies, researchers may switch their role between being an outsider and being a facilitator or group member (Punch, 1998). My facilitator role as a researcher was slightly different for

the treatment group as compared to the control group for the purpose of implementing the different instructional approaches. Both groups received the same amount of instructions in terms of conducting activities and progressing through the learning materials. My interactions with participants was not based on providing content answers but rather providing more technical guidance for both groups. The main difference for the treatment group was if participants ask a question or need my help with conducting the activities, then I provided the necessary guidance, which prompted their model-based reasoning. I asked some questions in response to their questions to encourage them recognize the connections between concepts or phenomena. On the other hand, if any participant in the control group asked a question or needed my help with running activities, then I gave them guidance, which helped them to solve that particular problem.

As an outsider, I took informal notes of my observations of participants' engagement during learning activities. These notes might not be enough to evaluate learning progress, but they documented my insider perspective for the data analyzing process.

As a researcher, I was responsible for collecting /organizing data accurately as well as storing data securely. Furthermore, I made sure that participants' names were replaced with identification codes and that their responses and video/audio records were transcribed and destroyed after 3 years. Finally, I analyzed the data and report the findings as part of my researcher identity.

4. STUDENTS' PRE-INSTRUCTION MODELS

A scientific theory is a representational system, re-presented externally mainly in its mathematical formulations, and, in some way, internally in the mind of those who understand it. Thus, an interesting research and instructional question refers to which internal representations students have—those corresponding to their alternative conceptions as well as those possibly constructed from formal instruction. (Greca & Moreira, 1997, p. 712)

As Greca and Moreria (1997) stated learners' internal models for scientific models determine what they know and how they learn. Students construct coherent and logical models that may be naïve, scientifically correct, or scientifically incorrect (Bao & Redish, 2006; Vosniadou, 1994). These initial models provide a basis for students to conceptualize new information about the world in which they live (Redish et al., 1998; Schwarz et al., 2009). Per diSessa (1993), students tend to use *phenomenological primitives (p-prims)*, which are reflected in students' very simple explanations of physics concepts and lack of solid reasoning. In DiSessa's (1988) work, p-prims were defined as a small well-developed and fragmented intuitive ideas. The research into students' understanding of quantum mechanics indicates that undergraduate students who had taken quantum mechanics (or modern physics) courses still demonstrate, despite instruction, a conceptual understanding at the level of p-prims (Johnston, Crawford & Fletcher, 1998; Kalita & Zollman, 2007; Singh, 2001; Wittmann, Steinberg & Redish, 2002). The analysis in this chapter will show that first-year physics and engineering students' pre-questionnaire responses agree with these studies. Furthermore, students' models reflect their incoherent and simple reasoning.

In the present study, students represented their models in different forms during the think-alone and think-aloud processes of the pre-questionnaire. The common models used by students include some aspects from a deterministic perspective (particle model) and some from a probabilistic perspective. I call this model that consists of elements from both quantum and classical mechanics, the “hybrid model.”

In this chapter, I present the students’ initial conceptual models in four categories, defined according to research conducted about undergraduate students’ understanding of quantum mechanics as well as an analysis of student responses to the pre-questionnaire of this study (see Table 4.1): (1) discrete entity (particle) model, (2) hybrid model, (3) quantum-like model and (4) quantum model.

Table 4.1: Descriptions and Subcategories of Four Types of Student Model about Fundamental Quantum Concepts

	<i>Description</i>	Examples			
		<i>Atomic structure</i>	<i>Electron motion/attribution</i>	<i>Energy levels/Atomic spectra</i>	<i>Use of terminology</i>
Discrete entity (particle) model	Students demonstrate a pre-mature understanding of the atomic model.	• Planetary/Bohr • Valence shell	• Fixed/specific location • Particle (point-like charge) • Electron as classical wave	• Absorption & emission as independent events • Quantization depends on number of electrons	• Wrong use of terminology
Hybrid model	Some level of sophistication is included in students' answers but answers have the essential components of the classic mechanical view.	• Orbital-Bohr/orbital-valence shell • Wave-Bohr	• Orbiting/zooming in shells • Orbital-valence shell representation	• Energy levels as reason for absorption & emission • Ground state as final destination	• Lost in terminology
Quantum-like model	Students in this category have a probabilistic view with some incomplete understanding or use of terminology.	• Orbital/even probability distribution	• Vague or incomplete representation of electron arrangement • Wave and particle as separate identities	• Lack of association between absorption/emission and atomic spectra • Emission follows absorption but must be one level at a time	• Fragmented knowledge or use of terminology
Quantum model	Students represent sophisticated models with meaningful explanations.	• Shell/subshell representation	• Probabilistic approach (probability distribution) • Wave-particle duality • Complete electron configuration	• Complete representation of atomic spectra • Absorption is followed by emission and any jump is possible	• Accurate use of terminology

Students exhibiting a discrete entity (particle) model demonstrate a conceptual understanding of atomic structure in a planetary or Bohr-like model. They draw a nucleus at the center and an electron or electrons on circular paths around the nucleus. Electrons are depicted mostly as negatively charged particles. Additionally, students' knowledge of energy levels and absorption/emission is fragmented. Students using a hybrid model exhibit a level of sophistication in their answers but also demonstrate the essential components of a classic mechanical view. For example, a student describing an atom under the hybrid model may mention orbitals, electron clouds, and the unclear positions of electrons. Even so, they still draw an atomic model with an electron or electrons located on circular paths around a nucleus. Students using hybrid models also indicate a fragmented knowledge concerning the emission and absorption of photons. Even though students know of these two phenomena, they commonly make mistakes concerning the sequence of events and energy level transitions. Student who exhibited quantum-like models had a probabilistic view when describing atomic structure and electron behavior. However, their models still showed some incomplete understanding or use of terminology. Finally, students who demonstrated a quantum model, which is the target model, produced sophisticated models with meaningful explanations. Unfortunately, in the pre-questionnaire, none of the students demonstrated the quantum model across any of the questions.

4.1 Atomic Structure

Several different questions on the pre-assessment asked students to describe and draw hydrogen and multiple-electron atoms. Almost all students (N=7) initially sketched a hydrogen atom that included aspects of the Bohr atom and of orbital representation.

One student simply showed a planetary/Bohr model with a nucleus in the center and an electron following a circular path around the nucleus. However, students who mentioned orbitals and electron location probabilities across different questions failed to properly explain their models of atoms. When it came to representing multi-electron atoms, most students had an incomplete understanding of atomic structure and, hence, inconsistent models. Those students demonstrated a circular atom model and located the electrons either on or inside circular orbits. Only three students showed some evidence that they knew about quantum numbers and orbital representation. The students' models of atomic structure and their descriptions are presented in Table 4.2.

Table 4.2: Students' Atomic Structure Models

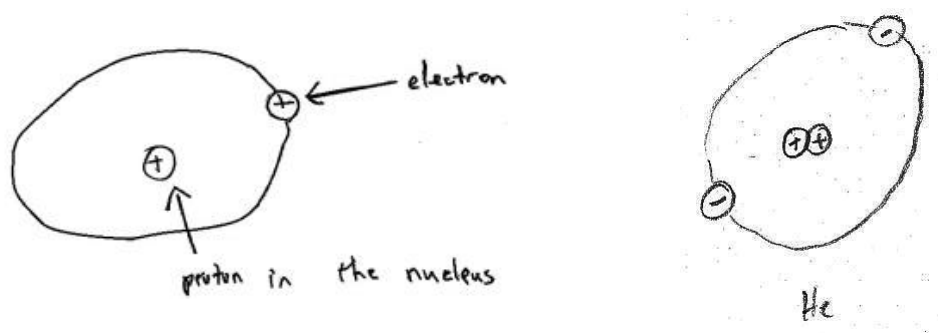
Type of Model	N	Atomic structure description
Discrete entity (particle) model	1	Planetary/Bohr model: Consists of one nucleus and electron(s) around a circular orbit
	1	Valence shell model: Consists of one or two circular orbits with electrons located on the circle(s) based on Lewis dot structure
Hybrid model	4	Orbital-Bohr/orbital-valence shell model: May consist of s and p orbitals, but electron(s) are located on the surface of a sphere and sphere is referred to as the electron's distance from the nucleus
	1	Wave-Bohr model: Consists of a Bohr model with de Broglie wave theory
Quantum-like model	1	Orbitals/even probability distribution: Consists of full orbital representation, but no indication of probability density (N=1)

4.1.1 Discrete Entity (Particle) Model

Students who used a discrete entity model described the fundamental quantum phenomena in terms of pre-quantum mechanics theories—i.e., a classical mechanics view. There were two common models that students used that indicated a discrete entity model: the planetary/Bohr and valence shell models. Out of eight students, only two students articulated discrete entity atomic models.

Planetary/Bohr Model

Among all the subjects of this study, one student's depiction of an atom was an example of the Bohr (or planetary) atomic model. The Student, T4, drew a nucleus in the center with an electron circling around the nucleus (see Figure 4.1). His model was consistent for both a hydrogen (single electron) atom as well as a multi-electron atom.



a) Hydrogen atom model

b) Multi-electron atom model

Figure 4.1: Student T4's atom models from the pre-questionnaire

As shown in Figure 4.1a, student T4 drew hydrogen and helium atom models including protons labeled with positive charges and electrons labeled with negative charges. He did not mention neutrons when he listed the components of a hydrogen atom. In general, the lack of neutrons in a hydrogen atom was very controversial for most of the students whose models were categorized as discrete entity models. They assumed that a hydrogen has one electron and one nucleus which includes one proton and one neutron.

Transcribed below are excerpts from the pre-interview with Student T4 concerning the question about describing a hydrogen atom.

I: ... The second part of the question says “draw a hydrogen atom and label all the parts”. So, you drew a positively charged... what is that?

T4: Proton.

I: A proton... the nucleus... Okay. So, you drew a positively charged nucleus and then here I see an electron. Is it positive or negative?

T4: Negative.

I: Okay, it is negatively charged. And what is that circle?

T4: It is not in the center. It is floating around it.

For a hydrogen atom, the student used the term “floating around” to describe the electron’s motion. His multiple-electron atom model showed similarities to the hydrogen atom model. Unlike hydrogen, however, Student T4 thought a helium atom could be positive, negative or neutral depending on the number of protons, electrons, and neutrons.

I: ... describe and draw an atom with multiple electrons. So, here there are two positively charged...

T4: Protons.

I: Protons. And then two negatively charged electrons around it. Is that right?

T4: Yeah.

I: So, is this a helium atom?

T4: Yeah.

I: And you said it can be positive, negative or neutral. So, what do you mean by that?

T4: Alright, the atom depends on how many protons and neutrons and the electrons it has, because it can be an ion also.

I: So, helium can have different amount of electron?

T4: I am not sure about helium since it is a noble gas, but I think other ones can.

...

I: So, here in helium atom there are only two protons and two electrons, is that right?

T4: Yeah.

I: There is no neutron?

T4: I mean it can have neutrons, but I don't know how many would have.

The student's response showed that he had some uncertainty with regards to the number of neutrons and the ionization of an atom. Therefore, he preferred not to include neutrons in his model of the atom. When Student T4 was asked about the motion of electrons in a helium atom, his answer showed some inconsistencies within itself and in comparison to his description of a hydrogen atom:

I: So, how do you think that electron is moving in the atoms? Like these two electrons? How they are moving?

T4: I think just... if it is a sphere, they can just go anywhere around the sphere wherever they want.

I: Is there any kind of order that we can determine the electron?

T4: Well, they have to be different distance, I think. Otherwise, like in the first shell, they can be so far and then second shell they have to be so far, further [he showed with his hand]. But I don't know.

I: Are you talking about the distance from the nucleus or distance from each other?

T4: Distance from the nucleus for the shells.

I: How about distance from each other?

T4: I don't think that's... I don't think that matters.

When describing a hydrogen atom, Student T4 indicated that the electron is “floating around” a circular path; however, when describing a helium atom, he was uncertain about electrons' paths. Yet, he still thought that electrons move around the

nucleus and used the term shell to define a circular path. Based on his explanation, the distance of the “shell” from the nucleus is important for an electron’s location, but not the distance between electrons.

Valence Shell Model

The second discrete entity model exhibited in students’ pre-instructional responses was the valence shell model. The analysis of students’ responses revealed that students were using models that they had constructed in chemistry courses regarding electron shells and valence shells. When asked to describe a hydrogen atom and electron configuration, students tried to recall related knowledge from a chemistry course that they took in high school or college:

M3: I thought of chemistry immediately, and then I was kind of doubting myself that there is one proton, one neutron in the nucleus, and there is an electron circling it. So, when I saw that question, I had a picture of hydrogen atom in my mind. And then I tried to relate it back to chemistry, but last time I took chemistry was two years ago. So, I should remember something about hydrogen bonds, and I remember the spectrum that our teachers showed us before.

T2: ...I don’t know. I learned this part in chemistry, like 115 or something. But it was last semester, so I forgot it.

Student M3 used her chemistry knowledge to describe a hydrogen atom and the electron’s motion. Although she could not exactly remember the information that she had learned in chemistry two years previously, she said that she remembers hydrogen bonding and the atomic spectrum. Student T2 similarly indicated a knowledge deficiency, as it had been a semester since he took his last chemistry course.

One student out of eight depicted an atomic model like the one represented in chemistry resources to demonstrate Lewis dot structure (See Figure 4.2).

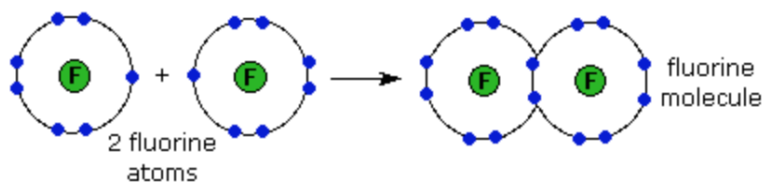
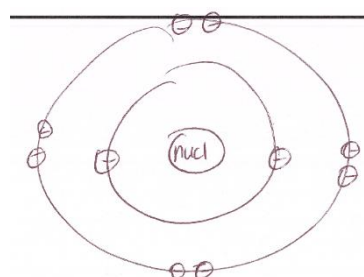


Figure 4.2: An example of a Lewis dot model of covalent bonding

Student M3 drew a hydrogen atom with a nucleus at the center, where a proton and neutron were located (like a planetary model). An electron was drawn on a circular line that she labeled as a “valence shell” (see Figure 4.3a). Her multi-electron atom model indicated that she thought electrons were located in different “shells” (see Figure 4.3b).



a) Hydrogen atom model



b) Multi-electron atom model

Figure 4.3: Student M3's atomic models from the pre-questionnaire

When asked to give details about her drawing of hydrogen atom, Student M3 describe the fundamental compounds of a hydrogen atom:

M3: ... this was the nucleus and then this is the electron going around.

I: Ok. So, in the hydrogen atom, there is one proton?

M3: Yeah

I: Is this a neutron?

M3: Yeah

I: ...one electron, and a proton and neutron in the middle of a nucleus and the electron kind of like goes around?

M3: Yeah

I: So, what is that line? Is it electron's motion or path?

M3: Yeah, no, I don't think it goes around like a circle, but that is like the place that you would most likely find the electron. So, you would not be able to find it in between different shells but you would only find it there. Yeah...

I: So, we are not sure if the electron is exactly here, but we know that the electron is moving around the...

M3: The shell...

Even though Student M3 drew a circular orbit and said “the electron moves around the shell,” her model of electron motion was ambiguous and mostly used components from a deterministic view. Although she used the phrase “most likely find the electron,” she pointed to a specific location when she drew electrons. This confusion showed that she had heard about possible locations for electrons, but applied it to a determined position in her model. In accordance with Bohr's theory, she indicated that electron shells are discrete, not continuous (electrons could be found on shells, not in between).

For the multi-electron atom, Student M3 modeled a neon atom that has 10 electrons. Based on her model, the first shell takes two electrons and the second shell takes eight electrons. Student M3 referred to a chemistry course that she had taken in her junior year of high school when she described the multi-electron atom model. Her verbal explanation showed that she was confident with arranging electrons in the first two shells:

- I: Why do you think these electrons are paired up but those are like three electrons together? Why did you draw two electrons here together and here three electrons together?
- M3: For ... if you just ignore the outer ring like the inside part, I am just trying what I remember from the chemistry junior year. Then, I remember that's how we drew in junior year. And then, for the last shell, because I think it goes from like 2 electrons and then 8, and then 8, and then I am guessing that it is 8, but I feel like I remember that after that, it changes to bigger number. So, that's why after filling in the 8, I did not move on to the next shell. I just kept going with the remaining number of electron that I have left.

After the second shell, she did not draw the third shell. Instead, she added the extra electrons next to the electron pairs until she had no electrons left. Her model of the atom was incomplete and incoherent within itself. Locating a “third” electron on the second shell increased the number of electrons on the second shell to nine, which is not possible according to her model of electron arrangement. However, Student M3 was still comfortable with drawing a ninth electron on this same shell. Her classical perspective overrode her reasoning.

4.1.2 Hybrid Model

A common feature among hybrid models is that students' ideas include pieces from both classical mechanics (or the discrete entity model) and quantum mechanics, which is a newly-formed uniform model. Students who use a hybrid model demonstrate both consistent and inconsistent understanding and reasoning about atomic structure depending on the questions and context. Two common models were identified as combinations of the discrete entity model and the quantum mechanics model. These are the orbital-Bohr or orbital-valence shell model and the wave-Bohr model.

Orbital-Bohr/Orbital-Valence Shell Model

Two dominant models that combined Bohr and orbital models emerged from students' responses. Although some students tried to explain atomic structure with quantum theory, they still used a Bohr model to represent either the atom or its components. Among the participants in this study, the orbital-Bohr model seems to be the predominant idea rooted in students' minds ($N=4$). One of the students drew a hydrogen atom with an electron located in a circular area and labelled it as a 1s orbital (see Figure 4.4a). However, her multi-electron atom included some characteristics which are similar to early atomic models (see Figure 4.4b).



a) Hydrogen atom model



b) Multi-electron atom model

They are present in 99% of the atom

Figure 4.4: Student M1's atom models from the pre-questionnaire

In both models, Student M1 demonstrated orbits with entwined circles. She indicated that electrons are not going around the nucleus; instead, all electrons stay completely inside the lines and occupy most the area of the atom (like the Thompson model). Her conceptualization of an atom showed inconsistencies, both in her atom depictions and her explanations. While she said that electrons could be found inside the circles, she drew an electron on one of the multiple circles of her hydrogen atom;

- M1: Yeah, I drew a.... the electron. It is spinning around the outer. And then the nucleus has the proton and neutron.
- I: Okay. What is that circle? Like a pathway of an electron?
- M1: Umm... the electron does not have to go that way. The electrons can be anywhere in the atom. Like they actually occupied like 99% of the atom and the one percent belongs to the nucleus which is a proton and neutron. So, this can go around like anywhere.
- I: Why did you draw these lines?
- M1: I drew it because umm... it just makes more sense to me put it on the outside because I know with electrons you wanted to... you want to utilize them and quantized them. And that just... I don't know that is how I am always used to putting them.
- I: Okay. And also, you put like the electron in the middle of the line. Not on the surface or not...
- M1: Hmm, hmm... No, no, no it has to be inside the atom.

For the hydrogen atom, she said, “[it] has one electron” and wrote $1s^2$ to indicate the electron configuration. This finding suggests that Student M1 had an incomplete understanding of electron configurations and quantum numbers. Presumably she used a $1s^2$ configuration without thinking what the values 1, s, and 2 represent in terms of quantum numbers. When Student M1 was asked about electron arrangement, she appeared to correlate electron's arrangement energy levels without mentioning quantum numbers or any rules/principles (e.g. Pauli exclusion principle):

- I: Okay is there any specific regulation for an electron should be here or here?
- M1: Umm ... as far... I know that each atom has like levels. So, like that [she drew levels]. This would be the highest level and this would be like second highest, third highest and this would be like the lowest. So, it depends on like if the energy is absorbed or emitted from the electron. But in this case, I guess I made it to the highest state.
- I: For a hydrogen atom, do you think the electron can be in the highest state?
- M1: No because it has only one shell, right? Or it can be... I don't know I forgot how to do the orbitals. So, I think it should be in a highest state, because ...
- M1: I think if I'm not wrong I think is s-squared the hybridization shell... Oh no, it will be in the lowest state, because it would be $1s^2$

I: Okay. So, do you know why it should be in the lowest state?

M1: No, there's no state. There is like one state in a hydrogen atom.
[laughs]

I: Okay. That means in the hydrogen atom, that does not have these different circles.

M1: No, no, no. It would one... yeah, there is only one circle or one level.

When asked if there are any specific rules governing the arrangement of electrons in an atom, Student M1 mentioned energy levels, emission/absorption, and orbitals. Her explanation indicated that she believed the circles are a representation of energy levels. Moreover, she thought that there was only one shell in a hydrogen atom in which an electron could be located, since it has only one electron. Her response showed that her model of energy states was incomplete and not scientifically accurate. Student M1's multi-electron atom model was similar to her hydrogen atomic structure model:

M1: So, I drew many electrons. And this is the nucleus inside with the proton and neutron. I said they are present in 99% of atom. So, they are like happily rooming around.

I: Okay. So why this time are there a lot of lines around the nucleus and electron?

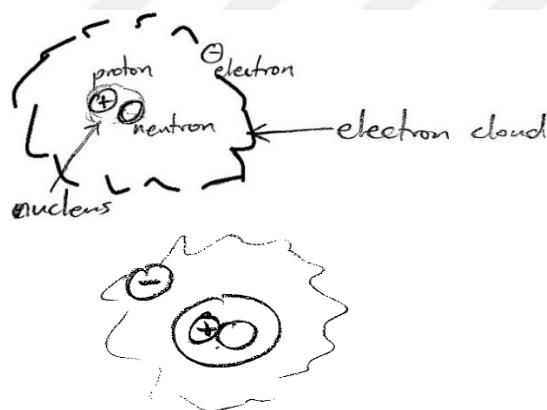
M1: Umm... I guess what I tried to do by that was I tried to represent like different levels. But in kind of a messy way.

This part of the interview with Student M1 illustrated that she reasoned that different numbers of energy levels were connected to the number of electrons; a hydrogen atom has one energy level, a multiple-electron atom has multiple energy levels. However, her model of a multiple-electron atom did not show the relation of energy levels to the electrons. The electrons were depicted inside the multiple interwoven circles. Student M1 clearly stated the disconnect between different concepts in her model of the atom. She said electrons occupied almost all of the area in an atom

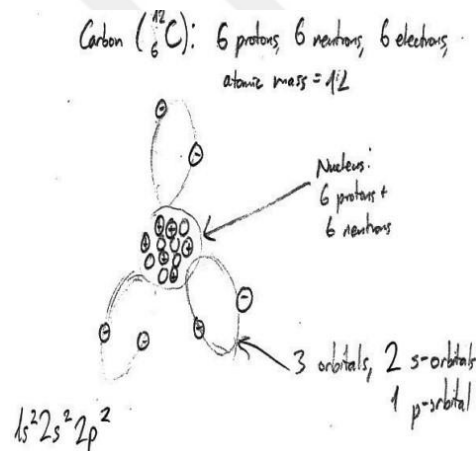
(99% of the atom) and she used the phrase “happily rooming around” the nucleus to describe the electrons’ motion.

Wave-Bohr Model

Analysis showed that students constructed orbital notions based on fragmented and unconsolidated understanding. For instance, students combined the de Broglie wave theory with the Bohr atom theory in such a way that their new models did not exactly reflect either of those theories. One student presented a wave-Bohr model to describe a hydrogen atom, while her multiple-electron model showed evidence of an orbital-valence shell understanding. This student’s initial hydrogen and multi-electron (carbon) atom sketches are shown in Figure 4.5.



a) Hydrogen atom model



b) Multi-electron atom model

Figure 4.5: Student T3's atom models from the pre-questionnaire

Both Student T3's hydrogen and carbon atom models have nuclei that include neutrons and protons. She drew a wavy “electron cloud” around the nucleus for the hydrogen atom; however, wavy orbit representations did not appear in her multi-electron atom model. Rather, she drew three water-drop shaped “orbits” that were attached to the

nucleus of the carbon atom. The electrons were paired and were located on the water-drop shaped orbits. The inconsistency in Student T3's understanding of atoms led her to construct a mixed model. Below is an example of her reasoning about hydrogen atom and electron's location model during the pre-questionnaire:

T3: There is nucleus in the center, there is one proton and one neutron, and there is an electron cloud with one electron. It is in some sort of probable orbital.

I: What does "electron cloud" mean?

T3: The region where the electron is probable to be. And it is because of Schrödinger, it can be everywhere once technically, probably, I think...

I: So, you drew a picture here. Can you explain that picture a little bit?

T3: Umm... nucleus in the center nucleus [inaudible] square ... I think maybe the cloud is somewhere. It is certainly interrelated nucleus is very, very small relative to the distance of the electron from the... And that due to the positive or the... not positive forces electron. There is some reason that the electron does not come to nucleus. I cannot remember why.

I: Okay. What's this kind of like wavy shape description?

T3: A cloud or probability. I just skip all that because it is not a definite orbit. It is not a circle.

I: So, for example for an electron in a hydrogen atom again, is there any possibility that we can determine the electron's position in anywhere around the atom?

T3: You can determine the probability of being in a certain position, I think.

Student T3 claimed that the distance between the protons and neutrons is smaller than the distance between an electron and the nucleus. Her reasoning about why atoms do not collapse into the nucleus was connected to the electronic forces inside the atom between protons and electrons; however, she could not describe the reason behind it with certainty. Concerning the wavy orbital, she defined it as "probability" or a cloud and emphasized that it is not a circle. Although her statement concerning the location of the electron in a hydrogen atom sounded like the target model, she could not present a

detailed explanation that illuminated her reasoning to support her statement.

- I: Ok. So, here we asked you to draw another atom with multiple electrons. And you came up with this shape, which is like a triangle...
- T3: Yeah, I know this cannot be right because the p has the different shape than the two.
- I: What do you mean that p has different shape?
- T3: I think... because p is bigger obviously. So, one of them has to have... well, there is not enough space for 6. But I am not sure what happens and it has only 2. I don't remember what causes the orbital stay different shapes.
- I: So, this is which orbital then? Which one is the p?
- T3: I don't know it just needs to have to be 3.
- I: Okay. Which one is s or how is the s orbital?
- T3: It can be any of them. I don't know.
- I: Okay. So, those are protons and neutrons? And...
- T3: I know how nucleus works, but outside of that there is puzzle.

Student T3 indicated her uncertainty about her multi-electron representation. She said that the p orbital's shape should be different than first two orbitals [1s and 2s]. She claimed that the p orbital should be bigger than the s orbital. Her reasoning for her electron arrangement was quite incomplete since she could not explain how different orbitals take different numbers of electrons, although her electron arrangement was correct. The concept of orbitals and their shapes was not clear for Student T3, so she depicted all the orbitals with the same shape. Assumedly, she thought that three oval shape orbitals represent 1s, 2s and 2p.

4.1.3 Quantum-Like Model

Students in this study did not demonstrate a complete quantum mechanics model before the intervention. Only one student's atomic model was close to the quantum model, consisting of full orbital representation but with no indication of probability density.

Orbital/Even Probability Distribution

When talking about electron locations in an atom, Student T1 referenced a probabilistic approach, however without mentioning probability density. Figure 4.6 presents Student T1's hydrogen and multi-electron atom models.

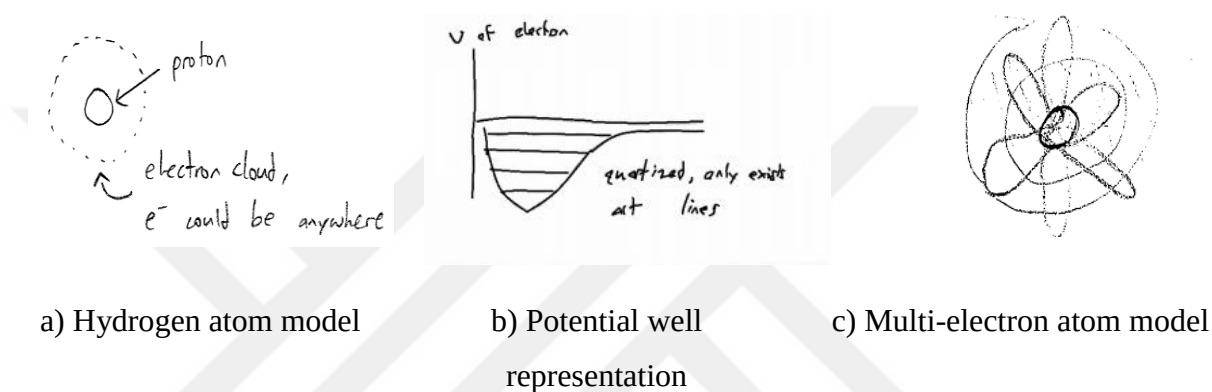


Figure 4.6: Student T1's depictions of electrons in an atom

In his hydrogen atom model, Student T1 represented an orbital, depicting the border of the orbital with dashed line. He described the area between the nucleus and the dashed border as an electron cloud and stated that the electron could be found anywhere in that area (see Figure 4.6a). He also drew a potential energy diagram where he showed possible energy levels (see Figure 4.6b).

T1: Umm... I kind of went with the whole orbital concepts again, saying that it does not follow a specific orbit. I said that the electrons are what are involved in an interaction between other atoms in like a chemistry thing like that. They are not like definitely stuck to the atom. That and they exist in quantized energy levels. As like they can have only specific values for their energy. This is all the same atom and these two circles are representing different orbitals. One of the electrons when it gets excited it can move up to a different orbital.

Student T1 used the terms “orbital” and “electron cloud” alternately to describe

the atom, and the two circles that he drew represented different orbitals. Based on his explanation, the potential energy graph also indicated these quantized energy levels:

T1: Umm... that is a graph of potential energy of an electron in the atom. I was not sure about the shape of that. Although I know that the electron can only exist at like where these lines are. Like as it going to have certain value for its potential energy.

I: Ok. How about kinetic energy? Electron's kinetic energy?

T1: hmm. when it's excited it would make sense that it is moving faster if it is further away from the atom. So, maybe instead of a potential energy this is just a total energy of the electron. I think that is more correct.

I: So, what you said is if an electron is excited, it goes further from the nucleus, and its motion is getting faster?

T1: Umm... well, it could still exist anywhere like within the orbital, but what I know about momentum and orbits like, even though this is like kind of a sporadic motion. If it is further away, you think they it would need to be moving faster. I mean if it is occupying a larger orbital than on average it would be further away. And so for the average kinetic energy then it would be larger. Although its kinetic energy seems like it would constantly be changing depending on where it is a relative to the proton.

I: Okay. So, the average kinetic energy is going to be larger. How about the potential energy? Is it going to be larger as well or what?

T1: If it is farther away there would be more potential energy, because it's an attractive force between the electron and the proton. And as those get farther away just like with gravitational potential energy. There is more potential for it.

Regarding the question of an electron's energy (potential vs. kinetic energy), Student T1's response indicated that he understood the relationship between an electron's potential energy and its distance from the nucleus; however, his knowledge was fragmented. Specifically, he was confused about whether an electron possesses potential, kinetic, or total energy as a factor of its position in an atom. Initially, he thought that electrons have potential energy, but later he changed his reasoning to the idea that electrons have total energy. That reasoning led him to another puzzling thought process concerning an electron's speed relative to its distance from the nucleus. Student

T1 said electrons move faster when they jump up to more excited states (higher energy levels). Although he had the idea of the undetermined position and motion of an electron, his reasoning concerning the relation between electron energy and velocity showed pieces from a deterministic approach. For instance, he made an analogy from a classical view of energy and velocity transformation. When I asked about his multi-electron atom depiction, he mentioned 1s, 2s, and p orbitals and their shapes (see Figure 4.6c).

T1: ...With multiple electrons, how I would draw that is I would make the orbitals and then shade them... Like the 1s orbital is a sphere. I just know that I just shaded and showing that it can be of any of those. And the next is the 2s orbital. And that occupies a lot of the same space as the 1s. And then the p orbitals look something like these. And then you would have these on all of the axes. And then all those are shaded and then it just turns into a mass of like probability pictures. Kind of all in the same spot and not necessarily to scale. How should I know the scale?

Even though Student T1 did not talk about specific orbital names and the probability of finding an electron in a location in an atom, he used the term “probability” for the area he shaded in his atom model. Based on his depiction, probability density is evenly distributed throughout each orbital.

4.1.4 Section Summary

In this study, two students’ initial atomic models were categorized as discrete entity (particle) models. While one student indicated a planetary/Bohr model, the other student had a valence shell model that included pieces from the Lewis dot symbol representation introduced in chemistry courses. Pre-questionnaire results indicated that a

hybrid model of atomic structure, which is inspired both from classical theories and from quantum mechanics, seems to be the prevailing concept among students, even those who complete quantum mechanics courses ($N=5$). While four students combined the Bohr model with an orbital or valence shell representation, one student mixed the Bohr model with a wave representation. These students argued that an electron does not follow a circular path in the atom and mentioned s and p orbitals; however, their explanations included essential pieces of the Bohr model. In the pre-questionnaire, only one student depicted s and p orbitals correctly and talked about the probability of finding electrons in specific orbitals. However, he did not emphasize probability density.

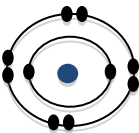
Electron position was one of the concepts that was very counterintuitive for students. Since students are not generally introduced to probability when learning classical physics concepts (Bao & Reddish, 2002), they have difficulty interpreting probability density and probabilistic ideas. Even though the students in this study were aware of the probabilistic approach and talked about probability density, they mostly failed to transfer this information when talking about electron attributes in different orbitals.

4.2 Electron Motion/Attribution

Based on answers to a question that asked students to provide a detailed explanation of electrons and of their behavior in an atom, students demonstrated very vague ideas about the specifications of an electron, such as its attributes, motion, and shape. Only one student's concept of an electron was based only on a discrete entity

model; the majority of the students' ideas fell into both the discrete entity and hybrid models, and a few fell predominantly into the quantum model.

Table 4.3: Student's Electron Motion/Attribution Model

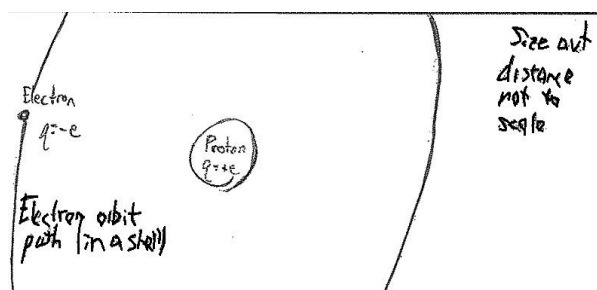
Type of Model	N	Electron Motion/Attribution
Discrete entity (particle) model	6	Fixed/specific location model: Electrons are positioned in fixed locations
	3	Particle (point-like charge) model: Electrons are depicted as negatively point-charged particles
	1	Electron as classical wave: Electrons are depicted as sinusoidal or zigzag waves
Hybrid model	3	Orbiting/zooming in shells: Electrons are described as orbiting or zooming around
	2	Lewis dot symbol representation: Electrons are represented as small dots located on circles based on the Lewis representation
		
Quantum-like model	1	Vague or incomplete electron arrangement representation: Arrangement consists of s and p orbitals but these are not ordered with appropriate quantum numbers
	1	Wave and particle as separate identities: Electron is either a particle or a wave, but cannot be both
Quantum model	2	Complete electron configuration: Arrangement consists of s, p, and d orbitals and these are arranged with appropriate quantum numbers

4.2.1 Discrete Entity (Particle Model)

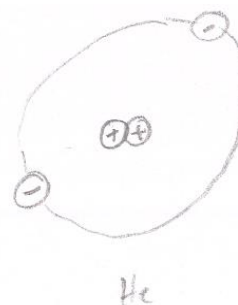
Until modern physics concepts are introduced, pre-college students learn about electrons as particles that are negatively charged and located on a circular orbit. Teachers/instructors prefer to use this model as a simple and convenient way of representation. Students start constructing a particle model of electrons from a very early age; this becomes a robust model even though most of these students will learn wave-particle duality later in more advanced courses. In most cases, students firmly hold onto a particle and fixed location model. In this study, most students used fixed and located particle models to define electrons and their positions. Two students, on the other hand, mentioned wave-particle duality and the probabilities of finding electrons in orbitals, but one of them still drew electrons in fixed locations as negatively charged points. Only a few students talked about wave-particle duality and showed the probability densities of where electrons could be found instead of drawing the electrons themselves.

Fixed/Specific Location Model

As part of the Bohr model, students conceptualized electrons as being located in specific positions. Six out of eight students drew an atom with electrons positioned on an orbit. Three of these students referred to “potential locations” or “probability clouds,” but their reasoning in connecting these terms to their models was not complete. Student M4’s and Student T4’s initial electron models are shown in Figure 4.7.



a) Student M4's electron position model



b) Student T4's electron position model

Figure 4.7: Students' electron representations

When students were asked to draw a picture of an electron, nearly two-thirds of the students drew an electron in an orbit. Unless specifically asked about electron position or motion, they did not mention a probability function. Student M4 depicted the electron on an “electron orbit path in a shell” (see Figure 4.7a). Student T4, on the other hand, drew two electrons on the same circular orbit (see Figure 4.7b). Below, an excerpts from Student M4's interview shows his both discrete entity (particle) and hybrid models in his description of atomic models.

M4: Umm... The electrons are orbiting at a distance is based on energy electron higher energy electrons would be further away usually. And there are only a certain number of electrons in each shell.

...

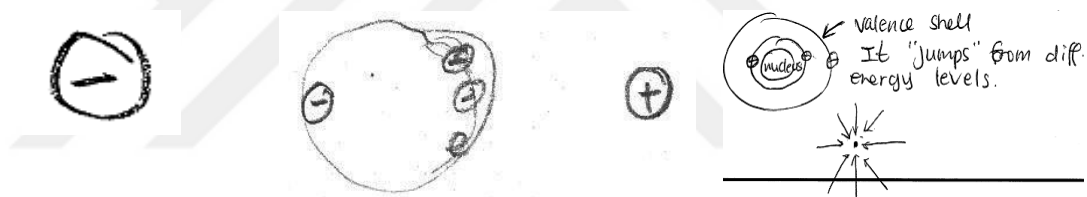
M4: So, the nucleus is there, probably a lot smaller but... and then there are much larger distance than what is shown here. I guess the electrons would be at different energy levels. So, there be ... maybe one orbital there and then the second one farther away. And then depending on how many electrons there are...

In the excerpts, Student M4 argued that an electron is located a certain distance from the nucleus depending on its energy. He said that if an electron has higher energy it stays further from the nucleus. He also emphasized the size-scale ratio of the nucleus

and energy levels. Based on Student M4's verbal explanations, the distance between the nucleus and the first energy level is much larger than that represented in his drawing.

Particle (Point-Like Charge) Model

In parallel with many studies, I found that a few students in this study thought electrons are point-like charged particles ($N=3$). These students modeled electrons based on electrical charges. This idea led one participant to generate an atom model where electrons have accumulated on one side of the atom due to the attraction force of a proton (Figure 4.8b).



a) Depiction of an electron by Student T4 b) Depiction of an electron and proton by Student T4 c) Depiction of an electron by Student M3

Figure 4.8: Students' electron representations

Figure 4.8a shows Student T4's electron model representation. This specific model is also an example of how most of the students drew an electron. Student T4 imagined that an electron has a negative charge and a spherical shape. Transcribed below are excerpts from the pre-interview with Student T4 concerning the question about describing electrons in an atom:

T4: I said they [electrons] have negative charge. And they are one of the three basic building blocks of atoms.

I: What does that mean?

T4: Like atoms are usually made of the protons, neutrons and electrons. And those are like usually basic and the last one I said they are

always around the nucleus if they are free.

I: So, what does that mean if they are free? Is there any possibility that they are not free?

T4: I think, I am not 100% sure but I am pretty... I think they can like... just if they are excited enough they can just leave. So, you get like ions and stuff like that. So, positively charged ion something like that.

...

T4: I mean if they are not free, they are around the nucleus. If they are free, they can be somewhere else. Yeah, I meant to say.

I: Okay. So, why they are around the nucleus if they are not free?

T4: Because the positive charge of the proton attracts the negative charge of the electrons.

Student T4 used the analogy of “building blocks of atoms” to define electrons, protons, and neutrons. He said that if an electron gains enough energy it can escape from an atom; otherwise, it stays in orbit around the nucleus. The same student used the phrase “floating around” when he described electron motion in the first question. On the other hand, he said that an electron might be “spinning around” in answer to the second question. Based on his model, the reason that an electron stays around a nucleus is the electric force between the positive (proton) and negative (electron) charges.

Figure 4.8c shows another student’s depiction of an electron (Student M3). This student drew an electron as a negative point-like charge with electric field arrows toward the charge itself. The excerpt below are excerpts from the interview with Student M3 concerning the question about describing an electron illustrates that she had very general information about electron:

I: What is an electron and how do you draw it? If you want to show me an electron, how would you show it?

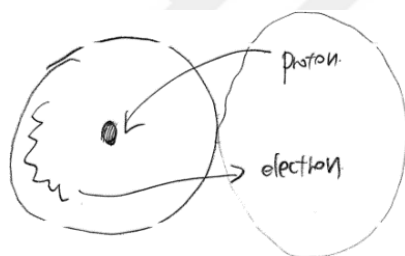
M3: It is a fundamental particle. So, you cannot break it down to smaller parts. And then it has a charge on it. It has negative. That means umm... the electrical charge on it attracting things. So, it would look like this. [She drew point like charge with arrows inward to charge.]

She emphasized that an electron’s indivisible nature defines an electron as a

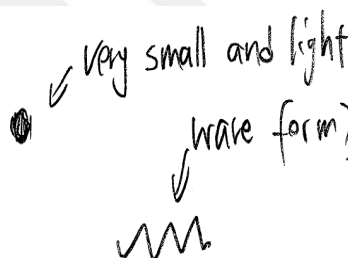
fundamental particle. She also related the negative charge of an electron with electrical charge and added that electron was “attracting things,” presumably referring to positive charges.

Electron as a Classical Wave

Most students’ understanding of the duality of an electron was incomplete. While many students represented electrons as point-like particles or spherical shapes, a few students depicted electrons with a wave. One student drew an electron with a classical wave shape in his depiction of a hydrogen atom. In Figure 4.9, Student T2’s hydrogen atom and electron models are presented.



a) Hydrogen atom model



b) Electron models

Figure 4.9: Student T2's electron model

His electron wave illustration looks like a sinusoidal wave, a representation that appears equivalent to that of classical waves, and which reflects a deterministic perspective. When Student T2 was asked about why he drew wave shape for electron depiction, he showed some ambiguity in his understanding of particle-wave duality:

T2: That wave is supposed to be the electron. I am not sure if I am supposed to like draw the same small circle or an energy wave or something like that. I am trying to memorize it. I cannot remember.

I: So, like the wave electron whatever you drew in here. You think it is located right here?

T2: No, it is like a cloud inside. It is like a possibility of being there. Like electron cloud or something like that.

Student T2 imagined an electron as having two different identities: particle and wave. When he was asked why he drew two different representations for an electron he referred to his high school online course as the foundation of his model, but he could not clearly and confidently explain his reasoning. While explaining his drawings, he was not sure which depiction was appropriate to use for an electron. When he was asked about the location of an electron wave in a hydrogen atom, he mentioned electron clouds and possible locations of electron waves.

4.2.2 Hybrid Model

As displayed in Table 4.3, hybrid models were the second most common theme in students' descriptions of electron attributes. The analysis of the students' responses revealed two types of commonly used hybrid model. These are the "orbiting/zooming in shell" and "orbital/valence shell" representations.

Orbiting/Zooming in Shells

To the question concerning an electron's motion in an atom, while three students used the term "orbit" when they talk about the possible locations of an electron., one student used the term "orbiting" to refer to an electron's unpredictable motion. Thereby, orbit seems to be a subsidiary notion that students use in different ways. The analysis of the data revealed that three out of eight students used this particular model. As an example of model representation, Student M4's depictions of an electron in specific orbits are shown in Figure 4.10.

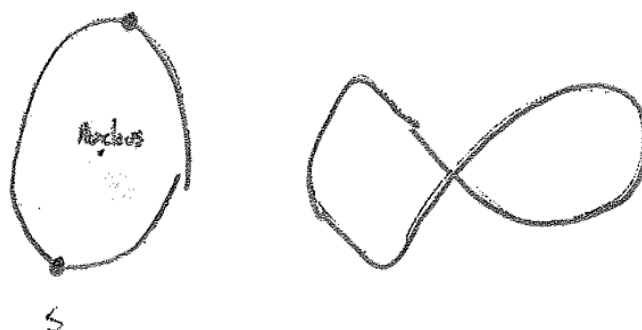


Figure 4.10: Student M4's depiction of an electron

When Student M4 was asked to explain electron arrangement, he mentioned s, p, d, and f orbitals and the limited number of electrons in each shell (see Figure 4.10).

Transcribed below are excerpts from the pre-interview with Student M4 concerning the question about describing electrons in an atom.

- I: Here we want you to describe an electron with the drawings. So, you actually described it as nucleus and a shell here? [shows drawing in Figure 4.10]
- M4: That was just trying to remember what the possible shells were. And so that was just s shell.
- I: s shell, okay. So, do you know about the other shells? Or shapes?
- M4: I vaguely remember... I think p shell... I think... Something vaguely like this, except more 3-dimensional. And then d and f I do not remember at all.
- I: Okay. How about electron's shape? What do you think which shape it should be?
- M4: I could not say for sure...
- I: Or what an electron is?
- M4: If I had to guess, I would say something about quarks but I don't know.

Student M4 displayed a partial understanding of s and p shells; however, he could not describe how many electrons each shell can take. While he described the shapes of s and p orbitals, he was not able to give any details about d and f orbitals. Concerning electron structure, he made a guess about electrons being made of quarks. In addition to his vague answers about electron arrangement, motion, and structure, he did

not say anything about electron shape. Although he used these terms to discuss electron location, he still showed some evidence that he had a discrete orbital (Bohr model) picture in his mind.

M4: Umm... the electrons orbit the nucleus at some distance like in the drawing. In higher electron shells, I think the orbitals are s, p, d, and f, I think. The orbits are a bit more complicated in the higher orbits, but I could not tell you what those are specifically.

...

M4: The electrons are orbiting at a distance is based on energy electron higher energy electrons would be further away usually. And there are only a certain number of electrons in each shell.

I: How do we know how many electrons should be in each shell?

M4: I could not say for sure.

Based on Student M4's response, electrons can be described as orbiting at some distance from the nucleus. In response to probing questions about electron motion, Student M4 responded, "It is somewhat random." The characteristics of these two answers indicate that he did not have in mind a consistent model of how an electron behaves inside an atom. Furthermore, he was not sure how many electrons can be found in a shell or how they are arranged.

I: Okay. So, what do we know about electron's motion?

M4: It's somewhat random umm... hard to describe at least. In the s shells, it is just kind of possible orbits are just sphere. Ones the electron has higher energy, it's harder to describe the motion, because it could be in a more complicated three-dimensional shape.

Structurally, his answers about orbits and shells were very ambiguous. In particular, he reasoned that an electron's motion was hard to describe in an s shell, but it is even harder to know at higher energy levels since they are three-dimensional shapes. In other words, his model of an electron's motion depended on the shape of the orbital.

Orbital-Valence Shell Representation

From chemistry courses, students are familiar with representations of valence electrons in Lewis symbols. Students who had learned orbital representation later in physics courses tended to mix these two representations. The analysis of students' pre-interviews showed that two students represented the orbital-valence shell mixed model. Below, Student T3's drawing is given as an example.



2 orbitals, 2 electrons

They orbit the nucleus at a large radius (relative to the size of the nucleus) in different orbital shapes depending on the # of electrons.

a) Student T3's electron model

b) Student T3's written explanation

Figure 4.11: Student T3's electron representation

Student T3 articulated her atom model representation around a wave-Bohr model, showing a wavy-shaped orbit around a nucleus and one electron located on this wavy orbit (see Figure 4.5a). However, her model of electron arrangement looked like an orbital-valence shell mixture. She also mentioned two orbitals (without mentioning s or p orbitals) with two electrons in each, 180° apart from each other (see Figure 4.11). With this statement, she reasoned that the 180° separation between electron pairs was due to electrical force. The following excerpt demonstrates an example of Student T3's reasoning and argumentation.

T3: They are far away from the nucleus, and stay in that way. And the moving orbitals they are not necessarily the orbits they are certain cloud or region that is far away from the nucleus, but stay in the certain range. Probably

- I: Okay, so what determines that certain range?
- T3: Umm... the number of other electrons around the atom. Because they are the same example from each other.... pretty strongly
- I: For example, for hydrogen atom, what do we know about the distance of electron from the nucleus? Since there is only one electron
- T3: Umm... it's closer than it would be if there is a lot of electron, I think. I cannot remember exactly what forces causing to push certain interactions.
- I: So, let say in that atom there is another electron somewhere around the nucleus. So, what would be the distance change from the one electron in an atom?
- T3: One electron, they try to stay in generally 180 degrees from each other on each side, right? One electron would be over here [she showed the atom diagram] and then one electron could be in the cloud over here [she showed the opposite side of the electron on the drawing] like this sort of and there... because they want to stay away from each other I guess their distance from the nucleus would increase. Because they be also avoiding each other not just the nucleus.
- I: Ok. And if there are three electrons then what would be their...
- T3: It is 120 degrees then? This is not the triangular... they are triangular [inaudible]
- I: What can you tell about the motion of electron?
- T3: Mostly randomly around the cloud which is why you cannot really predict where is it in a given point. Because it is moving around very very rapidly around its cloud of probability.

Although Student M3 acknowledged that electrons do not orbit around the nucleus, rather they are in certain regions or clouds, her depiction of electrons in an atom indicated an inaccurate model in which electrons are located at fixed positions 180° apart from each other. Furthermore, she added that if there were three electrons in an atom, the angle between the electrons would be 120°. Her reasoning for the relationship between the number of electrons and the distance of the electrons from the nucleus was shown in her belief that the single electron of a hydrogen atom was closer to the nucleus than the multiple electrons of another atom because of some forces she could not define. The incoherency in her understanding was also seen when she used the

term “moving around” after saying that electrons move “mostly randomly.”

4.2.3 Quantum-Like Model

In this model, students’ answers predominantly reflected quantum mechanical explanations and representations, but several components of their models and explanations were still not quite complete. The evidence in both visual and verbal representations showed that there were some logical errors in students’ ideas that they tried to fill from a classical mechanics viewpoint. I identified two main models from students’ representations of electrons: 1) vague/incomplete electron arrangement representation, and 2) wave-particle duality as two separate identities.

Vague or Incomplete Electron Arrangement Representation

In answering a question about how electrons are arranged in an atom, only one student showed an accurate understanding of s, p, d, and f orbitals and what those orbitals represent; however, they either could not write out the electron configuration in full or they wrote it incorrectly as their knowledge of quantum numbers was limited. Furthermore, none of the students could write orbital notation. Student M2’s model of electron configuration and orbital notation is shown in Figure 4.12.

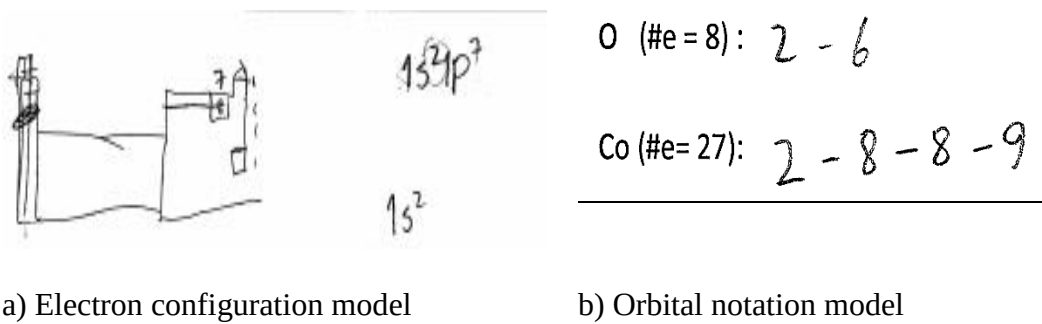


Figure 4.12: Student M2’s electron arrangement depiction

Student M2 used a sketch of the periodic table to determine the electron configuration of a fluorine atom, which has nine electrons (see Figure 4.12a). Although his reasoning to determine whether fluorine is in the s, p, d, or f column was correct, his knowledge concerning how many electrons are found in each orbital was insufficient. For the same reason, he also could not write out a krypton atom's electron configuration, which includes 36 electrons. When asked to write orbital notation for oxygen and cobalt, he wrote only the number of electrons that each shell can take (see Figure 4.12b).

M2: Okay. Umm. So, following the electron configuration rule, there is ... umm... hold on... [He drew an outline for periodic table]. It is fluorine somewhere there... Helium... and so that's 1s2 line... 1p and it goes to seven electrons in the outer shell. So... wait I mean... Yeah, 1s and then... So, there's 1s and then straight to this. Hmm. So, this 1s2 and then umm... Does it p comes first? That's 2 and then I guess it's something p7, because there should be seven electrons left. So...

I: So, what is that 1 representing?

M2: That's the means the first as shell which would be the hydrogen helium. Because that's one electron, two electrons. And then...

I: What does that s mean?

M2: It is just a symbol that we put for the particular type of shells, I think.

I: Okay, how about this "2"?

M2: That's the number of electrons in those shells.

I: Okay. And then p comes, right?

M2: Yeah

I: So, is there any kind of number before p?

M2: Yeah, there should be, but I cannot remember if it was 1 of 2. I feel like it should be 1, because it is the first one, but then I'm just a little bit lost because it is hydrogen, helium... Carbon, nitrogen, fluorine... So I guess, it is 1p because it is the first one.

I: Okay, So, is it all for fluorine?

M2: Yeah there is 9, so that's what it adds up to.

I: Okay, so how about krypton?

M2: And krypton is... umm... that's helium, neon, argon, krypton... So that's 36 and that's the full shell. So, that's 1s2 and then... I cannot remember how it exactly goes.

His method of determining the electron configuration by referring to the periodic

table indicates that he associated each column of the periodic table with one orbital (recalling chemistry classes). However, his knowledge of quantum numbers and what they represent was limited. When he described his electron configuration model, he showed hesitation concerning whether p orbits come after s orbits. Furthermore, he thought that p orbits start in the first shell after 1s. Although Student M2 did not mention quantum numbers specifically, his presumptions for principle quantum numbers and orbital angular momentum indicated a sophisticated understanding of electron arrangement. Concerning the question about showing orbital notation, however, Student M2 said that he was not sure if orbital notation was different from electron configuration. After I clarified that it is a different representation of the same idea, he talked about how many electrons can exist in each orbital:

M2: Is orbital notation same as the electron configuration or is that some different one?

I: It is a different representation of the same thing.

M2: Okay. Umm...

I: Do you have any idea about what orbital notation is?

M2: Is that just how many electrons are in each orbit? Or...

I: Something like that.

M2: So, would that be like 2-6 [electrons], because there's just two in the inner and there is six in the outer. Okay... So... and then in that case there would also be 2-8 [electrons] and that 17 [electrons] left. And another 8 and then 9 [electrons]. I don't know if that is correct notation.

His reasoning about orbital notation indicated that he used the valence electrons accommodated in each valence shell. He did not mention orbitals in each shell like he did in the previous question (electron configuration). He only talked about the number of electrons in each shell.

Particle and Wave as Separate Identities

Another aspect of students' non-normative models was the conceptualization of the wave and particle features of an electron as separate identities. Students seemed to interpret the particle and wave features of an electron as two different identities that the electron chooses between based on the situation, but it will never be both. One student, Student T2, in this study held this model.

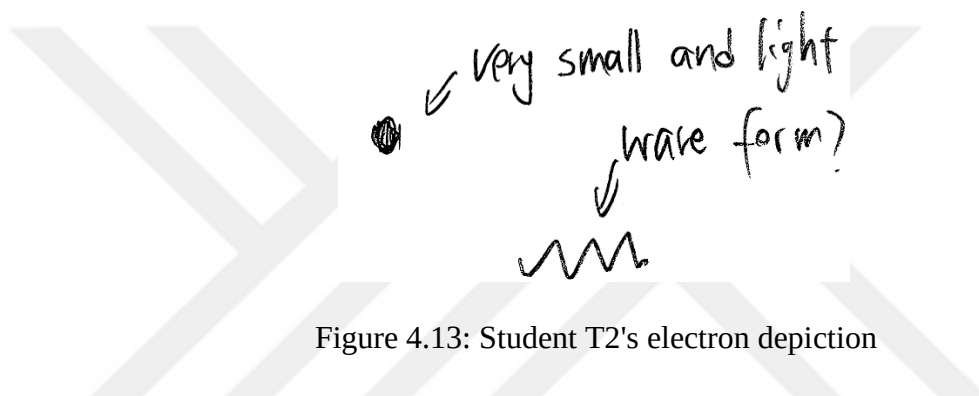


Figure 4.13: Student T2's electron depiction

Student T2 depicted an electron in two different forms, as presented in Figure 4.13. For the particle form, he described the electron as a very small and light particle. He drew zigzags to show the wave form of an electron. He, and other students who had this model, may have adopted this idea from textbooks or other resources where waves are shown as classical waves (see Figure 4.14).

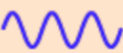
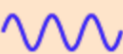
Phenomenon	Can be explained in terms of waves.	Can be explained in terms of particles.
<u>Reflection</u>	 ✓	 ✓
<u>Refraction</u>	 ✓	 ✓
<u>Interference</u>	 ✓	
<u>Diffraction</u>	 ✓	
<u>Polarization</u>	 ✓	
<u>Photoelectric effect</u>	 ✗	 ✓

Figure 4.14: Wave-particle duality: Light*

Below, Student T2 provided his reasoning for showing electron both as wave and particle:

T2: I just draw it with a circle and colored it.

I: Hmm... So why do you have two different representations?

T2: I am not sure. I learned this somewhere like in high school, like I took some online courses about this. I forgot what I learned, but I know like the ... like it is really small. Sometimes it acts like energy or something. I cannot remember, but I draw this to represent a...how to say...electron magnetic wave. I think I was... yeah

I: Okay. So you think that sometimes it acts like energy, and...

T2: Sometimes like a particle.

Student T2 indicated that he learned about the duality feature of electrons in high school, but could not remember the whole concept accurately. Furthermore, he could not clarify why he drew two different representations for an electron. He also said that an electron sometimes “acts like energy or something.” Later in his explanation, he argued that he meant electromagnetic waves in his wave representation. In general, wave-particle duality was one of the concepts that caused difficulties in students’ conceptual

* Retrieved on 03/30/2017 from: <http://hyperphysics.phy-astr.gsu.edu/hbase/mod1.html>

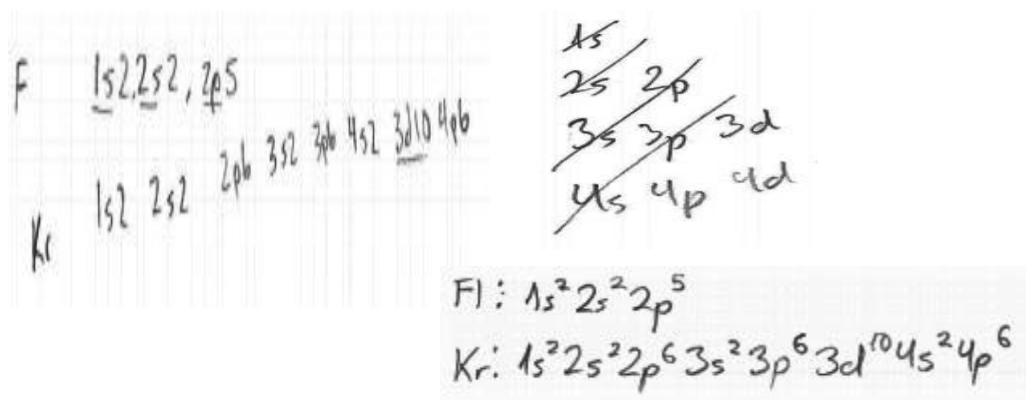
understanding. Students believed that electrons mostly act like particles and, from time-to-time, like waves, but never both. Based on classical mechanics, an object can only have one state in given conditions. It is most likely that students used this idea to explain electrons' dual nature. Therefore, it was a very common mistake that students identified an electron as either a particle or a wave.

4.2.4 Quantum Model

Using a quantum model, students were expected to depicted the concept of electron behavior from a probability perspective. Students whose models were assigned to this category demonstrated relatively scientifically appropriate understanding as their explanations mostly followed the standard quantum view of reasoning. Among all the students in this study, two students' explanations of electron arrangements were classified as quantum model, which I considered to be expert level understanding. These students showed a coherent understanding of electron configuration.

Complete Electron Configuration

Electron configuration concepts are generally first introduced to students in high school chemistry and/or physics courses. In these courses, students are introduced to quantum numbers and then to the Pauli exclusion principle, the Aufbau principle, and Hund's rule. The results of this study showed that the undergraduate participants could not remember either quantum numbers or any of the other principles to write electron configuration. Although two students were able to describe quantum numbers and write out electron configurations (ECs) correctly, they were not able to recall orbital notation.



a) Student T1's EC representation

b) Student T3's EC representation

Figure 4.15: Students' electron configuration models

Students T1 and Student T3 both wrote standard notation to represent electron configuration. On the question about orbital notation, Student T3 wrote the same electron configuration, while Student T1 could not remember how to represent it.

I: Can you just explain a little bit your reasoning [for electron configuration] here?

T1: Yeah, so the 1s and the 2s and the 2p those are describing like which of the orbital it is. And then the third number is the number of electrons in that orbital. And s orbital can hold a maximum of two electrons and p can hold up to six. And the order of the orbitals is something that I memorized and they correspond to I believe the energy that orbital is at. And for the electron is to be in that orbital. And krypton, you just do about the same thing as this. Except $1s^2 2s^2 2p^6 3s^2 3p^6 \dots$ I have to count quickly here. Okay, then next is the $4s^2$ and then $3d^{10}$ and then I assume $4p^5$ if that adds up to 36. Yeah there will be $4p^6$.

I: Okay. So, how do you know this order?

T1: I have it memorized in... it was actually in chemistry class. We... that's where I learned all of these and it is fairly logical for the most part, except for the fact that the 3d orbital is actually at a higher energy than the 4s.

I: Based on what?

T1: That was based off of... we were given a graph of the energy of all of the orbitals and we're basically just hold that does this one exists at a higher energy not really a reason why.

I: Okay. So, is there any method that you used to memorize this order or you pictured that graph that you were given and...

T1: I... usually, I picture the graph about for... things that have a very

small a number of electrons. I just can kind of reproduced it without thinking about it.

While Student T3 used the diagonal rule to find the correct configuration sequence, Student T1 said he had just memorized the order of orbitals. Neither of them mentioned any of the principles that govern electron arrangement in an atom. Furthermore, they could not remember how to write orbital notation even though they said they had learned it before. When they stated their reasoning, they confused orbital notation with electron configuration.

T1: Orbital notation. I know I've done it before but I don't know exactly what it's asking. Like, I am feeling like this [he showed his electron configuration for Kr atom] might be the orbital notation, right? or yeah like these phrases the electronic configuration and the orbital notation I might have them confused. I know that I have done this before and I know how to I just don't know exactly what it's asking.

I: For orbital notations, so you do the same thing?

T3: Yeah, I knew that thing right [she showed her electron configuration of Kr in the previous question] because it should have a close being Kr. It should have... it is noble gas. So, shells have a full orbital.

I: So, do you know what orbital notation is?

T3: Oh. The difference?

I: Yeah

T3: No I don't remember the difference

Student T1 was certain that he had learned and done orbital notation representation before, but he could not do it again when he was asked in the pre-test. He presumably would have known how to represent electrons in an orbit with spin-up and spin-down arrows if he was shown this notation during the interview. Student T1 could not recall the information because he did not learn that this representation is called orbital notation or because he forgot what he had learned. Student T3, on the other hand, was not aware that electron configuration and orbital notation representations were different until the interviewer indicated this. She confidently explained her model of

electron configuration for the question on orbital notation.

4.2.5 Section Summary

The types of answers given to the interview questions revealed that the students in this study held incomplete and/or scientifically inaccurate understandings of electron attributes such as structure, behavior, location, and motion. Although two students could explain electron behavior based on a probabilistic perspective, in most cases they indicated some deterministic aspects blended with probabilistic reasoning and explanations as their understanding was incomplete. The fixed position and particle nature of electrons were the most frequently represented ideas by freshmen/sophomore physics and engineering students. While two students demonstrated a sufficient understanding of different orbitals and their shapes (s, p, d, and f), one of them still showed some deficiencies in writing out complete electron configurations due to a limited knowledge of quantum numbers. None of the students were able to describe and represent orbital notation.

The nature of wave-particle duality appears to be a difficult concept for students to fully understand and recall. Most students in this study had a general idea about electrons' dual nature, but any further details were missing from their explanations. Students modeled wave nature mostly according to a classical perspective, even though the students held notions of probability of existence and electromagnetic waves are known.

One of the essential topics of a modern physics course is the double-slit experiment (Müller & Wiesner, 2002). The analogy with classical optics is generally

used in modern physics courses to introduce electron wave behavior (Vokos et al., 2000). In this study, a few students talked about the wave-particle duality of electrons, and their models were inspired by classical waves. They represented the wave nature of electrons with sinusoidal waves.

Even though two students mentioned wave-particle duality in different questions, when they were asked to describe an electron, they tended to depict a point-like particle without mentioning wave properties. Almost half of the students, on the other hand, did not talk about the wave properties of electrons at all. They thought electrons stuck to a nucleus' orbit and moved around it because of an electrostatic (attraction) force between the electrons and protons.

4.3 Energy Levels & Atomic Spectra

Energy levels and atomic spectra are two important concepts to examine to see if students can make the transition between early atomic models, the Bohr model and later quantum theory. To questions that asked about defining energy levels and corresponding atomic spectra, most students showed primitive understanding.

Table 4.4: Students' Models of Energy Levels and Atomic Spectra

Type of Models	N	Energy Levels & Atomic Spectra Description
Discrete entity (particle) model	1	Quantization depends on number of electrons: The number of energy levels depends on the number of electrons in an atom
	7	Absorption & emission as independent events: Excited electrons can stay in an excited state for an indeterminate time
Hybrid model	3	Ground state as final destination: No matter what the initial electron state was, once an electron is excited it always returns to ground state
Quantum-like model	3	Lack of association between absorption/emission and atomic spectra: A good understanding of how absorption and emission occur; however, there is a lack of association between transitional lines and atomic spectra

4.3.1 Discrete Entity (Particle) Model

In this category, students demonstrated partial understanding of the absorption and emission process, but their knowledge and reasoning were not sophisticated enough to correlate the sequence of phenomena by acknowledging the cause and effect relationship. Students frequently used two models to represent their reasoning for quantization and spectra. In the first model, quantized levels are dependent on the number of electrons in an atom. In the second model, absorption and emission are conceptualized as two independent phenomena.

Quantization Depends on Number of Electrons

The hydrogen atom is commonly used to introduce atomic structure and is represented mostly as having a spherical shape (either with a Bohr orbit or 1s orbital), as

this is the simplest atomic structure with a single electron. Therefore, students tend to reason that there is only one (the first) energy level where the electron can be found.

During the interviews, Student M1 changed her reasoning about quantized energy levels in a hydrogen atom while explaining the emission and absorption process.

I: So, how do they emit or absorb energy?

M1: They would receive energy from an outside source. Like maybe it may be another electron... maybe if another electron came by... it would emit energy because it wants to go to lower shell like it wants to go as far away from it. And then if a proton came then it will go to the higher energy because it wants to... because opposites attract. So, it wants to be with that proton.

I: Okay. Let me kind of rephrase what you said. If a proton comes to the electron and hits it, does it go to higher level?

M1: Yeah higher level.

I: What if an electron comes closer to that electron or hits it? What happens then?

M1: It will go to lower-level because it wants to stay away from the other electron

I: Okay. So, what can you tell about quantization in a hydrogen atom?

M1: Umm...well now that I realized that hydrogen only has one level. I don't think energy can be quantized. So, I change my answer.

Students M1's reasoning for absorption and emission was not based on a coherent understanding. First, she mentioned that exposure to energy from an outside source causes the excitation of an electron. She then talked about attractive and repulsive forces due to opposite or the same charges. She explained that the reason an electron would go to a higher level was the attractive force of a proton, and the reason it would go to a lower level was the repulsive force from other electrons. When she was asked about quantization in hydrogen atoms, she changed her response to the non-quantization of hydrogen atoms due to their single-electron atomic structure. Her reasoning for the causation of absorption and emission led her to incorrectly revise her existing model of quantization. Her new reasoning was that, since there is no other electron to repel a

hydrogen atom's electron, there could be no absorption or emission, and consequently no quantized energy levels in a hydrogen atom.

Absorption and Emission as Independent Events

Almost all the students (N=7) were not certain that absorption and emission are two consecutive events. In other words, they believed that an excited electron could stay in its excited state indefinitely. Two students were confident in their responses, but other students showed some hesitation in expressing their reasoning. Below the excerpts show two students' (Student T4 and Student T3) differing descriptions of the absorption and emission process.

T4: So, can be either of them? I don't think it stays there for an unlimited amount of time, but I think it can change depending on like levels of electrons around them.

I: ...So, I want to go back to the second one. You said that you were not sure if an electron could stay there indefinitely or not.

T3: I guess it is possible, you can say that.

I: So, you were saying that you are not sure?

T3: Not 100% sure. I would think it come back down if it has excess energy it does not want, but not for sure.

Student T4 initially said that an electron cannot stay in the excited state for an indefinite time, but then he said that the time an excited electron stays at a higher level depends on how many other electrons are around that electron. Likewise, Student T3 was uncertain as to whether or not an electron jumps back down right after being excited. Another student in the study, Student M1 also indicated an inaccurate model which separates the absorption and emission processes, as shown in the following pre-interview excerpt:

M1: ...Umm... after an atom becomes excited, the electron remains in the excited state indefinitely. Once it gets excited, I think it just stays there unless anything else happens...

M1: For this one [an electron in the $n=4$ state in the hydrogen atom moving to the $n=2$ state by emitting electromagnetic radiation at the appropriate frequency], I said an electron... yeah so it supposedly in the fourth state. This is the fourth state. It cannot go to the second state, which is this, it can emit. And then it can go there.

I: Okay, so, is it possible for an electron to go directly from 4 to 2?

M1: No, it has to go 3 first. It cannot just like jump.

I: Okay. So, it should kind of like follow the order. Like 4 to 3, 3 to 2, 2 to 1.

M1: Yeah

Student M1 explained that the absorption and emission process occurs when an electron receives and loses photons. However, she indicated that emission does not have to occur after an electron gains energy during the absorption process. Another model that she had in mind concerned electron transition during the emission process. She conceptualized that electrons jump one level at a time when releasing photons. The explanations of students across all the interview questions illustrate that they mostly used locally coherent but universally inconsistent structures.

4.3.2 Hybrid Model

Electron transition and the absorption/emission process are considered key concepts in understanding atomic spectra (Körhasan & Wang, 2016). The ideas presented as hybrid models came from students who conceptually grasped energy levels and the absorption/emission process but also had some inaccurate reasoning, which caused them to misarticulate spectral lines. I have identified one frequently used hybrid model employed by students.

Ground State as Final Destination

When students were asked to explain the emission of photons, three of them said that no matter where the electrons are located before becoming excited, they always return to ground level by emitting a photon of the appropriate specific wavelength. In the excerpts below, Students M2, M3, and T1 described their respective understandings about an electron's transition after becoming excited to a higher level:

M2: ...I think, because the electron can also emit light. Well, yeah, it can emit photon. So, at some point it would go back to ground state, I think.

I: So, what kind of jump is possible?

T1: Umm. It is most likely that it would go from 4 back down to the ground state.

I: Without going back to third or second level? Should it go directly to the ground state?

T1: Yes, although it is still likely for it to go from like 4 to 3 or 4 to 2. I am actually not too sure about this one because my professor last semester said that although it is possible, it is also unlikely that... basically says that it won't happen. Although it is technically possible.

M3: ... after an atom becomes excited, the electron remains in the excited state. Actually, this is false because I feel like I remember from PHYS1 that it would always like try to return to the ground state. I don't know why though.

I: So, what you are saying is that it does not stay in excited state, but it wants to go back to ground state? And you don't know what the reason is for that.

M3: Umm. I don't know, but if I have to guess, I think it is because that is the most desired state since that required at least energy to stay in. So, then after it becomes excited it will try to always go back to the one that is sort of state the most comfortable in. And that's how it won't stay in excited state indefinitely.

I: So, I have a question for that one. Is that possible for an electron to go from 4 to 2?

M3: I don't think so. I think when it is excited, it just goes back to ground state not to like second or third.

I: Ok. For example, if an electron is excited to the fourth state, then it goes back directly to the ground state, not the second or third one?

M3: Yeah. But then when it is other way around, like gets excited, I think

it can go from 1 to 2 and then 2 to 3 and then 3 to 4, but then when it is the other way around, when it releasing energy, it just goes straight from 4 to 1 or 3 to 1 or 2 to 1.

All three students' descriptions of absorption and emission phenomena indicated quite accurate level of conceptual understanding; however, it was not complete. They articulated that an excited electron jumps directly down to the ground state regardless of where it was before getting excited. The reason given for this jump was that all electrons want to be stable and the ground state is the most stable level. While Student M2 indicated that inter-state transitions are possible, Student M3 said that an excited electron always returns back to ground state, based on what she learned in a calculus-based modern physics course. Student T1 recalled that in a very small number of cases these inter-state transitions could occur. According to Student M3, an electron is allowed to make inter-state jumps when absorbing energy, however, it cannot make inter-state jumps during emission.

4.3.3 Quantum-Like Model

Students' responses in this category illustrated a high level understanding of energy levels and atomic spectra. However, the models were scientifically incomplete. The analysis of students' pre-questionnaire written and verbal responses revealed one common model that can be considered a predominantly quantum model.

Lack of Association Between Absorption/Emission and Atomic Spectra

Based on analysis, three students' initial models were found to be in this category. Students who used this model explained electron transitions well, but when they were asked about the dark lines that appear in the sun's atmosphere, they could not

explain that those lines represent absorbed photons by specific gases in the sun's atmosphere or, in the second case, by sodium.

M1: I kind of like sort of guess on this one. I just said that we are unable to [know] precisely what is happening there may be because of that frequency that we cannot see it. It's something that the human eye is not able to observe and you have to use may be a different kind of lens or something like that to be able to see it.

Student M1 clearly stated that she was making a guess to answer that question and she attributed the appearance of dark lines in the sun's atmosphere to the limitations of human eyes in seeing different frequencies. Student T3 indicated that she had not heard anything about dark lines before.

I: You don't have any idea about like how dark lines occur in the sun spectrum?

T3: I have not heard anything about that.

I: Okay. Here it is asking the comparison between the spectrum of the sunlight with the dark lines and the spectrum of the dark lines in the sodium lamp can identify that sodium is one of the elements in the sun's atmosphere.

T3: So, my guess was the dark lines appear at the same wavelengths. So, they have certain compounds, emitting something or not emitting something the same place.

I: But you don't know where these dark lines come from?

T3: No.

I: It is asking how a comparison between the spectrum of sunlight dark lines with spectrum of light from sodium lamp can identify that sodium is one of the elements in the sun's atmosphere.

M4: The sodium lamp will... sodium lamp functions by the electrons in sodium atoms moving from higher energy levels to lower energy levels and releasing photons that are equal to the energy difference, like I said before. And so that those photons describe the... that describes the difference in energy states specifically for sodium. So, the energy of those photons will correspond to the wavelengths that are missing from the sun's spectrum if sodium is in the atmosphere.

Student T3 could not explain the appearance of dark lines in the sun's atmosphere. In the second question, where she needed to compare the dark lines in the sun's atmosphere with the ones in a sodium lamp, she mentioned "they have certain compounds emitting something or not emitting something the same place." She associated dark lines with electron emissions. Likewise, Student M4 explained the dark lines in terms of photons released as electrons transfer from a higher energy level to a lower one. Although his reasoning that these dark lines were specific to sodium atoms was scientifically correct, he could not articulate his reasoning based on the scientific facts. Therefore, both students' models indicated an inability to transfer their knowledge of the emission and absorption phenomena into an understanding of atomic spectra.

4.3.4 Section Summary

The quantization of energy and atomic spectra are very important concepts for understanding quantum theory. In order to understand electronic states in an atom, transitions of energy (electron transitions), and orbitals, students are supposed to establish a fundamental understanding of energy levels and atomic spectra (Körhasan & Wang, 2016). The concept of discrete energy levels is widely accepted by students across multiple types of model, from discrete entity to expert level (quantum model). Even though four students depicted electrons according to the Bohr model, with a fixed electron on a circular orbit, or took a deterministic approach to the atomic model, they still showed evidence of being aware of the quantization of energy levels (or discontinuity of electron orbits). The interview results, however, indicated that three students had difficulty transferring their knowledge of energy levels to explain atomic spectra. Although the process of absorption and emission seemed to be clear for many

students, the relation between these two phenomena was still obscure. The main issue in students' initial models of atomic spectra was identified as the inability of students to transfer their knowledge of transitional lines to the concept of atomic spectra. A correct understanding of both electron transitions between different energy levels and emission/absorption energy does not seem to necessarily reflect a scientific understanding of atomic spectra.

The other two troublesome concepts that were detected were related to the absorption and emission process. The emission process was conceived as a phenomenon independent from absorption. Seven students thought that when an electron is excited it moves up to a higher energy level and stays there for an uncertain amount of time. Only one student indicated that electrons need to be stable and to achieve this will decay back to the lower states by emitting photons. Among these students, many of them believed that the stable state is always the ground state for every electron. Without considering the initial state of each electron, they believed that all electrons jump back directly to the ground state. Three students also claimed that no inter-state jumps are allowed, especially in the emission process.

4.4 Use of Terminology

Important evidence of a scientifically correct conceptualization is the correct use of concise and coherent scientific terminology, while incorrect reasoning or non-normative concepts are revealed with vague or inaccurate use of scientific words and terms (Henriksen & Angell, 2010). Quantum mechanics concepts introduce many challenges to students due to the unique and abstract nature of the terminology (compared with classic mechanics) and the complexity of phenomena. In this study, I

observed that students' use of terminology varied from a novice level to a predominantly quantum mechanics level when describing models of the atom, energy levels, and atomic spectra.

Table 4.5: Students' Use of Terminology

Type of Model	N	Use of Terminology Description
Discrete entity (particle) model	2	Wrong use of terminology: Students are familiar with certain terms, but they inaccurately use those terms
Hybrid model	5	Lost in terminology: Students are familiar with certain terms, but they show some inconsistency when they use terms in their descriptions
Quantum-like model	1	Fragmented knowledge or use of terminology: Students do not demonstrate a complete or coherent quantum understanding (for example: mixing electron configuration and orbital notation)

4.4.1 Discrete Entity (Particle) Model

Students whose conceptual understanding of fundamental quantum mechanics concepts reflects a classic mechanics perspective generally express their reasoning by using notation and terminology that they learned in introductory mechanics courses. In particular, orbit, orbital, shell, and other terms are used arbitrarily without meaningful explanation.

Wrong Use of Terminology

The analysis of students' responses indicates that the language used to describe quantum mechanics phenomena reflected students' scientific and non-scientific models. Only two students' uses of terminology were found in this category. The excerpt below from the interview with Student M3 shows her reasoning use of terminology from

chemistry course:

M3: I thought of chemistry immediately, and then I kind of doubted myself about whether there is one proton, one neutron in the nucleus and there is an electron circling it. So, when I saw that question, I had a picture of hydrogen atom in my mind. And then I tried to relate it back to chemistry, but last time I took chemistry was two years ago. So, I should remember something about hydrogen bonds, and I remember the spectrum that our teachers showed us before.

Here the student made an explicit connection back to a chemistry course that she took several years ago. She tried to remember the model of a hydrogen atom shown in the chemistry course. Therefore, she used some words learned in that course, such as “circling,” when she described the electron’s motion. Later, she switched her model of the atom back to something better reflecting the knowledge that she had learned in physics courses; she said it is impossible to determine an electron’s location. In her responses, it was also evident that the atomic structure and bonding model that she had constructed during chemistry courses confused her understanding of atomic structure and electron behavior from a quantum mechanics perspective.

I: Ok. Here we asked what quantization of energy means. So, what did you say?

M3: I remember teacher once said that quantum means like things are coming chunks. So, when I think of quantization in energy. It just tells me what we learned the spectrum like you cannot... you have to go from here to here [she shows her drawing of energy levels which is next to the question box] you cannot go in between or anything. It is like a package. You cannot break it down into smaller things. So, I think quantization of energy is like when electron go from shell to shell, they cannot be found between those, but they have to be found right there.

Student M3 explained quantization using general terms. For example, when she explained the quantization of energy, she used language and analogies from daily life.

Another noteworthy point from her response was that she described energy packages and energy levels without mentioning the term “photon” or any other specific terminology for the absorption and emission processes. She also used the term “shells” to describe energy transitions between different states.

On another question, Student M3 struggled to clearly explain her model of a multiple-electron atom due to the limited quantum terminology that she had. For example, to explain the multi-electron atom she said “outer ring” when describing electrons in the highest shell:

M3: For ...if you just ignore the outer ring like the inside part, I am just trying what I remember from the chemistry junior year. Then I remember that's how we drew in junior year. And then, for the last shell, because I think it goes from like 2 electrons and then 8, and then 8 [electrons], and then I am guessing that it is 8 [electrons], but I feel like I remember that after that it changes to bigger number...

On another question, she struggled to clearly explain her model of a multiple-electron atom due to the limited quantum terminology that she had. For example, to explain the multi-electron atom she said “outer ring” when describing electrons in the highest shell.

Similar to Student M3, Student M1 also appeared to refer her high school chemistry course when she explained hydrogen atom. The following excerpts show some of Student M1's use of terminology when she was asked to describe hydrogen atom:

M1: Umm... because I think if I'm not wrong I think is s-squared the hybridization shell... Oh no, it will be in the lowest state, because it would be 1s-squared

Student M1 used the phrase “hybridization shell” to refer to an excited state. From the beginning of the interview, she mentioned several times that her knowledge of atomic structure was based on what she learned in high school chemistry courses. Therefore, she confused electrons’ excited states with hybrid orbitals, which are mixtures of different atomic orbitals created when they overlap and form a new type of orbital.

M1: Electron shape... Umm... an electron is generally something that has a charge and it also gives... based on how many electrons a something has doubts how many protons would have as well and based on the number of electrons something has that’s how many protons it would have as well. And based off the number of electrons we can also determine the atomic mass and we can determine the atomic number. So, there is a lot of things we can determine just using how many electrons there are.

In response to a question that asked about describing an electron, Student M1’s verbal explanations consisted of very vague and unscientific terminology, such as, “...an electron is generally something that...” She also said there are many things that can be determined from the knowledge of the number of electrons in an atom, but she did not give any further details.

4.4.2 Hybrid Model

An analysis of students’ verbal explanations indicated that they mostly used hybrid models, which are largely unscientific but emerge from the combination of quantum mechanics and classical mechanics terminology. Hybrid terminology and unscientific models usually appear together, like a chain reaction.

Lost in Terminology

Students fitting this category showed knowledge of some quantum phenomena and tried to use the proper language to explain their understanding. However, their explanations indicated fragmented or inconsistent terminology, which was neither fully correct nor completely incorrect. Five students demonstrated this kind of mixed terminology in their explanations. Below, excerpts from the transcriptions of two students' interviews, Student T4 and Student T3 are presented as examples of hybrid terminology usage.

T4: I know Schrödinger means you cannot know everything about electron. I don't know if it is... these two are correct [location & spin]. If it is, you cannot predict both location and spin. Or you cannot predict both location and velocity.

Student T4's response to the question concerning Schrödinger's theory indicated some confusion with the Heisenberg uncertainty principle. He said, describing Schrödinger's theory, that it is impossible to know both electron velocity and location at the same time; he seemed confident in his definition.

In contrast, Student T3 was able to recall her previous knowledge of Schrödinger model and probability density. However, she appeared to confuse the scientific terms in her explanation:

T3: Umm... that, I think I remember from the electron cloud and the probability of electron being in certain location in space. So, I guess the density being the probability [inaudible] so like the density of the electron is being everywhere at once.

I: Okay. How about the wave function?

T3: I am not sure, but I would think that is an electromagnetic wave. But I am not sure I did not really learn that term in any context.

I: Okay. And how about the Schrödinger model?

T3: That's the everywhere at once. The cat is death or alive. So, the electron is everywhere in the orbital at one time. And not just in one

location. Because it is moving so incredibly fast. It is effectively and distributed through the entire cloud at once.

On the question about probability density, Student T3 described electron probability reasonably well, but she also said “the density of the electron is being everywhere at once.” Although the question was asking about probability density, she separated these two terms as different phenomena and defined each term independently. While her answer about probability was acceptable, her density definition revealed her unscientific model. Later, when she was asked about wave function, she made a guess and said, with uncertainty, that it concerns electromagnetic waves. Concerning the Schrödinger model, Student T3’s answer represented her incomplete understanding when she gave the example of Schrödinger’s thought experiment involving a cat to explain how an electron is effectively distributed through its entire cloud at once.

4.4.3 Quantum-Like Model

Student models in this category were closer to the target model but still incomplete. Although only one student, Student M2, could use quantum mechanics terminology properly, his explanations included some missing information or fragmentary elements.

Fragmented Knowledge or Use of Terminology

The student tried to explain some quantum phenomena and theories using proper terminology, however, he frequently indicated his uncertainty about the models and the use of some specific terms.

M2: Umm... probability density helps us guess where the electron is more likely to be. Or I guess, just any particle is more likely to be in that sense. I cannot remember how wave

function was related. I know like... wave function squared is related to the probability density, but I don't know what wave function actually was. I don't remember it. And Schrödinger Model ...umm...it might have to do with ... I remember reading about an experiment where we have an electron that's ... like a source of electrons that shoots electrons one at a time. And there's like a screen with two holes in it and there's a lot of back screen which detects electrons. And like it forms the interference pattern on the screen. And the problem was even though there's only one going through at a time the emit-interference pattern and there was an explanation that because we don't know which one it's going through, it's going through both of them at the same time. I don't know how that works, but... And I know Schrödinger made the famous Schrödinger's cat thing where he said like we can't tell whether the cat is alive or dead without observing it first. And I feel like that's sort of relevant to this, because we don't know which one it is going through until we observe it.

The language that Student M2 used to describe probability density was the basic and common definition used in different resources such as textbook and web-based sources. Although could not give a conceptual definition for wave function, he mentioned the mathematical model relating wave function and probability density. He also mentioned the relation of double-slit experiments and Schrödinger's theory in terms of knowing electrons' location when you try to measure or not measure them.

4.4.4 Section Summary

A student's demonstration of conceptual understanding of topics is dependent on proper use of scientific terminology. Terminology includes facts, laws, principles, and other notation that help scientists to define, develop, and communicate their ideas (Pushkin, 1996; Silisko & Dykstra, 1997). Students' use of terminology also gives us an opportunity to evaluate their models of abstract phenomena and their understanding.

As displayed in Table 5.5, five students' use of terminology in this study fell into the hybrid model category. Their verbal explanations included components from both quantum mechanics and a deterministic perspective. three of them used words such as orbital, orbit, shell, subshell, etc. interchangeably to describe electron attribution and motion. They mentioned that they had learned these words in previous chemistry or physics courses. However, the analysis showed that they either could not recall the precise meaning of these terms or they did not learn them properly at all. In their verbal descriptions, they mostly used very vague terms, such as "thing" and "something," or they used the same vocabulary they used in daily life.

Two students demonstrated inaccurate use of terminology throughout their pre-interviews. In particular, the notation used to explain quantum phenomena appeared to be challenging for students. Terms such as hybridization, shell, orbital, wave function, and probability density were utilized by students to represent their conceptual understanding; however, most of the terms were incoherently or improperly defined. Although none of the students in this study had a comprehensive understanding and usage of the terminology, one student showed a strong, if fragmented, knowledge of quantum terminology.

5. TRANSITIONS IN STUDENT MODELS AFTER MODEL-BASED INQUIRY

The second research objective of this study was to monitor the MBLM students' model alteration process via a qualitative case study approach. In this chapter, I will present each student's model development stages between the pre- and post-questionnaires. Out of a total of eight students, four were assigned to the model-based learning module (MBLM) group and were provided with a sequence of activities incorporating various types of models, including physical, virtual, mathematical, and graphical models. One of the students in the MBLM group (M1) did not complete all the lessons and associated activities. Therefore, I will present her model development process up to the last lesson that she was able to complete.

Analysis of the students' pre-instruction models of atomic structure, energy levels, and atomic spectra revealed that the students mostly used models reflecting deterministic or blended (a mix of deterministic and probabilistic) perspectives. Therefore, MBLM was implemented as a cognitive mediator to improve the model evaluation process. The four MBLM students were assigned to pairs and asked to come to a face-to-face meeting two times a week for four weeks, excluding the pre- and post-interviews. They usually completed each lesson and the lesson's associated activities over the course of the week (but occasionally in one day) and then completed an inter-lesson assignment, which consisted of four to six questions. In total, they were required to complete six inter-lesson assignments.

In the following sections, the students' pre-interview responses, their worksheets, their inter-lesson assessments, and finally their post-interview responses are analyzed

and reported. A careful analysis of the students' models and their model-based reasoning reveals their cognitive development as they gained new perspectives from different models.

5.1 Evaluation of Student M1's Model

Student M1 was a sophomore electrical engineering student during the spring of 2016. She took an AP chemistry course in high school and enrolled in PHYS1 and PHYS2 in two consecutive years in college. She reported that her high school chemistry course covered the concept of energy levels. Based on field observations, her motivation in this study was very low. In fact, most of the time she gave the impression that she wanted to complete the activities as quickly as possible and leave the sessions. Her engagement with activities was also very careless and result oriented; therefore, most of her responses were perfunctory and incomplete.

Student M1's atomic structure models, prior to the study, are shown in Figure 5.1.1.



a) Hydrogen atom model

b) Multi-electron model

Figure 5.1.1: Student M1's initial atomic models

Student M1's initial atomic structure models can be characterized as having relatively large nuclei and electrons, as well as having nested/intertwined circles around the exterior. Although she mentioned the s sub-shell in her hydrogen atom, she did not indicate it; she also did not draw her multi-electron atom based on orbital representation.

5.1.1 Lesson 1: Early Atomic Models

Early atomic theories were introduced to the students with five simple hands-on and computer-based simulations. The first model-based inquiry activity used Thomson's plum pudding model. Student M1 was asked to hold and investigate a foam ball without further engagement (i.e. without sticking a skewer into it). On the worksheet, she was required to first write her prediction for what would happen as skewers were inserted into the ball." She wrote, "*They would go through to the other side.*" Her prediction was straightforward and appeared to be based on a holistic approach.

After making observations with skewers, Student M1 stated, "*There is nothing but more of the white Styrofoam material inside the ball. It makes the same noise all throughout sticking the skewer in the ball. Also it gets stuck at certain areas in the ball, may be this is the nucleus.*" Her observational notes indicated that she located some objects when she inserted the skewers; however, she thought that these objects were part of the nucleus. Figure 5.1.2 shows her drawing of the Thomson model based on her observations.



Figure 5.1.2: Student M1's Thomson atom model

Her drawing supported her verbal explanation. Presumably, she drew and explained her model of the Thomson atom based on her prior knowledge of an early atomic model, which is most likely the planetary model. After engaging with a computer-based simulation, which allowed the student to simulate shooting alpha particles through the atom, she recorded on her worksheet, *“After hitting the atom, they go straight fast curved. The Δ in energy increased. The trace is in curved direction at the end.”* In her statement, she talked about the change in direction of alpha particles and the change in their energy, but she did not mention what these observations mean in terms of atomic structure.

In another activity, she was given some small balls and a ramp with two plates (negative and positive) at the end. The task was to determine the behavior and qualification of the balls. Before making observations, she was required to write down her prediction. She wrote, *“I would assume that it would just go straight b/c there are no charges present in the ball. If there was a charge, it would go to the negative side or positive side.”* Student M1 stated almost all possible conditions in her prediction. Unlike the other students, she did not mention magnetization or magnetic poles. After she rolled balls using the ramp, she reported, *“When I drop the ball, it curves and goes toward the positive charge, probably b/c the balls, for the most part are negatively charged.”* In response to the question about the relationship of this activity to electron motion, she said, *“When an electron goes through the + side of a plate and tries to get to the negative side, the kinetic speed will decrease b/c its trying to go to negative side. Visa versa from – to +, the speed will increase b/c it tried to reach positive plate.”* In her observational notes, Student M1 realized that the balls curved toward the positively

charged plate and she inferred that the balls were negatively charged. Her second statement, on the other hand, was a little confusing. She stated that when the electron tries to get to the negative side, its kinetic speed (presumably she meant linear speed) decreases, and vice versa. It would appear that Student M1 was trying to address the electrical field and the electrons' behavior in this field, but it was not a direct answer to the question.

The second set of activities were about Rutherford's atomic theory. As in the first activity, students were given a foam ball and were requested to make some observations without using any skewers. Student M1's prediction for the second foam ball was *"It would do the same thing as before. The skewer would go through the entire ball; however, if it hit a certain region, it would not go through entirely."* This time her prediction was more structured and was closer to the real conditions. After she made observations with skewers, she said, *"it does the same thing as the other model. It makes the same noise throughout."* She also drew the model presented in Figure 5.1.3.

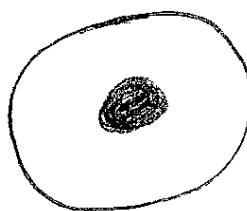


Figure 5.1.3: Student M1's Rutherford atom model

Although she said she observed the same thing as she did in the first model (Thomson model), her drawing indicated a different conception. She drew a large solid nucleus within the mass of the atom, as opposed to her previous diagram that included an empty space around the nucleus. From the model, it appears that Student M1 observed nothing else apart from the nucleus.

Another activity used to reinforce the Rutherford model was a Rutherford scattering simulation. Students were asked to record their observational notes using different nuclei. Student M1's observational note for this activity was "1. *When it is sent, they are moving in curved path* [when the number of protons and the number of neutrons are both 20]. 2. *Increasing the # of protons made the curve appear larger* [when she kept the number of neutrons the same but increased the number of protons]. 3. *Increasing neutrons made the curve smaller* [when she kept the number of protons the same but increased the number of neutrons]. 4. *It becomes faster, and gets closer to atom* [when the numbers of protons and neutrons are both increased]."

In this activity, Student M1 realized that when the number of protons increases, the angle of alpha scattering increases as well. In an inter-lesson assessment, one item asked students to explain the assertions of the Rutherford experiment. Student M1's answer was "*It asserts that the electrons are scattered throughout the atom, and the nucleus is in the center.*" She demonstrated a sound understanding of how Rutherford came to the conclusion that atoms have a heavy nucleus at the center.

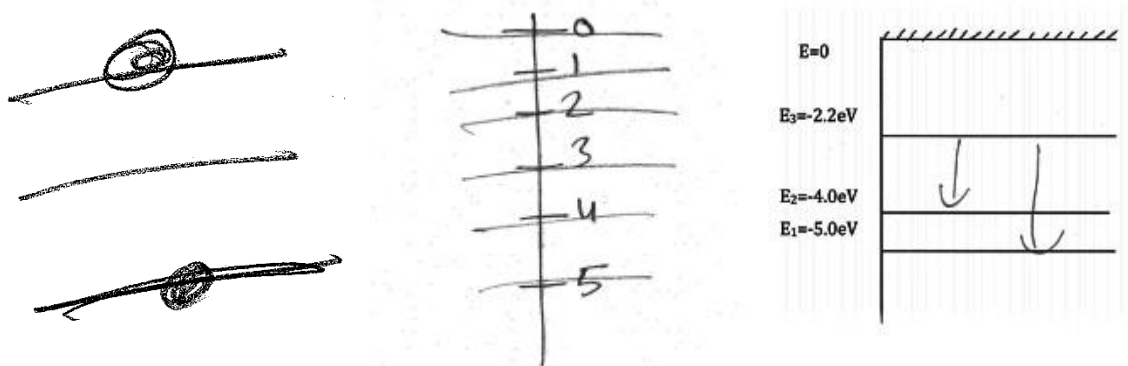
Another question in the inter-lesson assessment asked what would happen if you bombarded atoms with alpha particles if the Thomson model was correct. Student M1 responded to that question by writing, "*He expected it to go through in a straight linear like line. However, this did not happen.*" Her statement was correct but did not directly answer the question.

At the end of the first unit, students engaged with a simulation that showed a planetary model of the atom. Students were asked to record their observations in this simulation. Student M1 reported that "*It [an electron] moves in a circular path and then*

eventually it hits the center and explodes.” Student M1’s description of the planetary model was correct but insufficient. She did not reconcile her observation with her reasoning. In another inter-lesson assessment question, students explained the early atomic models and the reasons that they were successful and/or how they failed to explain certain atomic behavior. Student M1 answered that question by writing, *“I think they were successful in explaining, however, there were probably many theories about the atomic models. So, it may have been hard at the time to figure out which model is accurate.”* Her response to this question was unfortunately incorrect and was incoherent with her observation statement about the planetary atomic model.

5.1.2 Lesson 2: Energy Levels and Quantization

Student M1’s model of quantization, prior to the study, was mostly in the discrete entity (particle) model category. Her definition of quantization had subsumed some scientific ideas but was not a complete or ideal description of quantization. Initially, she was not familiar with electronic transition representation in her energy level diagrams. However, she started using the target model energy level diagram in an inter-lesson assessment. Figure 5.1.4 shows how Student M1 revised her model over the course of the study.



a) Pre-test

b) Worksheet

c) Inter-lesson assessment

Figure 5.1.4: The evolution in Student M1's energy level diagrams

The first diagram indicates that, in Student M1's model, electrons can be found at discrete energy levels and not in between these levels. In the second model, which was drawn during model-based inquiry activities, Student M1 showed electrons' energy corresponding to specific energy levels. Although the numbers were incorrect, she demonstrated an understanding of the idea of negative energy. Transcribed below are excerpts from the pre-interview with Student M1 about quantization and energy levels in an atom.

I: What does quantization mean?

M1: ... I think that means shells or levels of hybridization that are filled. Like I know there is s orbital, p orbital, d orbital. So quantization is basically what level it's on.

...

M1: Hmm ... as far... I know that each atom has like levels. So like that [she drew levels]. This would be the highest level and this would be like second highest, third highest and this would be like the lowest. So it depends on like if the energy is absorbed or emitted from the electron. But in this case I guess I made it to the highest state.

I: For a hydrogen atom do you think the electron can be in the highest state?

M1: No because it has only one shell, right? Or it can be... I don't know I forgot how to do the orbitals. So I think it should be in a highest state, because ...

I: It should be or it can be?

M1: I think I would say it cannot be

I: why?

M1: Hmm... because I think if I'm not wrong I think is s-squared the hybridization shell... Oh no, it will be in the lowest state, because it would be 1s-squared

I: Okay. Do you know why it should be in the lowest state?

M1: No, there's no state there is like one state in a hydrogen atom. [She laughed]

I: That means in hydrogen atom that does not have this different circles.

M1: No, no, no. It would one... yeah there is only one circle or one level.

I: So, in any condition, electron should be only in the lowest state?

M1: Yeah, in this state.

I: Okay. Do you know what the lowest state called?

M1: Hmm... I know that the one emits energy, it goes to the lowest state. But I don't know what the... Ground level! Ground level!

Although her explanation of quantization was not quite correct, it is fair to infer that she knew what quantization and energy levels were, based on her later explanations. However, her model was incorrect in asserting that the number of energy levels was dependent on the number of electrons in the atom. She stated that a hydrogen electron must have only one “circle,” or energy level, which is ground state.

Another interesting point about energy levels from Student M1's think-aloud process was how she conceptualized shells and subshells. She mentioned that 1s-squared is a hybridization shell but then changed her mind and indicated that 1s-squared is the lowest state. From Student M1's statements, it is obvious that she had conceptual confusion about the hybridization of orbitals and about electron arrangement in specific shells, sub-shells, and orbitals. In the inter-lesson assignment, she revised and refined her model of energy levels in an atom and stated that “*There are various levels to the states in an atom.*” Her initial model, in which the number of energy levels depended on the number of electrons, was superseded after model-based inquiry. She realized that an atom possesses many energy levels.

With respect to the relationship between energy, frequency, and wavelength,

Student M1 again indicated confusion, especially in her mathematical model.

M1: I think the longer the wavelength the less you can see it.

I: You said there is inverse relationship between frequency and wavelength. What do you think about energy and frequency? What should be the relationship between energy and frequency or energy and wavelength?

M1: Energy and frequency?

I: If you want to draw anything or write...

M1: Yeah, I think I will write down the equations.

I: Yeah just write it down

M1: I think that's the frequency equations [$w = \frac{1}{T}$]. As far as energy,

umm... we could do... No this is current [$iE = n u E$]. Umm... I don't know how to relate them... Oh wait! No I know... [$v = u E$ & $\frac{w}{s} = u E$] Okay. So, this is the equation I have [$v = u E$]. So, I know

velocity equals drift speed... no no this is mobility times... E field no it is not energy. Electric field. No, that's not energy. Okay then, I don't know.

I: Okay. What are those equations?

M1: So, this was what I tried to do... umm... was just I was listing equation that I am doing in my current class right now and try to find relationship, but, I kind of forget.

In response to a question about the relationship between energy, frequency and wavelength, she wanted to write down equations. Initially, she confidently wrote several equations; but, when it came to explaining those equations, she realized that they were not directly related to photon energy. After a couple of attempts, Student M1 gave up and said she was trying to remember the equations that she had just learned in her class, which I assume was one of the E&M courses.

After completing the model-based inquiry activities, Student M1 was able to define the relationships between energy, frequency, and wavelength. She wrote, "*Energy & frequency have an inverse relationship. Red has more light b/c lower energy, higher*

frequency.” In response to another question, she said, “*The longest wavelength is red... the shortest [wavelength is] violet.*”

5.1.3 Lesson 3: Atomic Line Spectra and Energy Levels

Student M1’s model of atomic spectra prior to the model-based inquiry activities was also at the level of a discrete entity model, like her initial model for energy quantization.

I: How they [electrons] emit or absorb energy?

M1: They would receive energy from an outside source. Like maybe it may be another electron... maybe if another electron came by... it would emit energy because it wants to go to lower shell like it want to go as far away from it. And then if a proton came then it will go to the higher energy because it wants to ... because opposites attract. So, it wants to be with that proton.

I: Okay. Let me rephrase what you said. If a proton comes to the electron and may be hits it, it goes higher level?

M1: Yeah, higher level, yeah.

I: Because you said the opposites attract each other and try to ... the protons try to put away this from other proton which the electron was kind of close before. What if an electron come closer to that electron or hits it? What happen then?

M1: It will go to lower level because it wants to stay away from the other electron.

I: Okay. What can you tell about quantization in a hydrogen atom?

M1: Umm...well now that I realized that hydrogen only has one level. I don't think energy can be quantized. So I change my answer.

I: That’s okay. You can leave it there. What happen do you think if an electron emits or absorb?

M1: When absorbs energy, it goes to higher level. When it loses energy, it goes to a lower level.

I: Okay. What happen to that energy? The energy that electron lose?

M1: I would want to say that it transferred to something else. Maybe like because I know kinetic energy plus potential energy equals work. So, when it goes to a lower [murmuring]... when goes to lower level it has a higher potential, because it can move... because it is in like the bottom area, right? Let’s suppose like we have like three levels, if an electron is on this level [ground level], there is no other place it can really go. So it has a lower potential. But if it was the first level, then it can move up like that. So, it would be easier for it to move. So I think that the energy is translated into kinetic energy.

- I: What happen if an electron jumps down from higher energy level to the lower energy level?
 M1: The energy is lost.
 I: Is there any other terminology that we use for that?
 M1: If it goes to the lowest level?
 I: Yes
 M1: That will be the ground level.
 I: No, no, what do we call that process? If an electron goes down...
 M1: Emit! Emit!

Student M1's explanations suggest that her initial model of absorption and emission was relatively far from the scientifically accepted model. She believed that an electron moves to a higher level due to the attractive force of a proton, and it goes to a lower level due to other electrons' repulsive forces. It is very difficult to interpret her reasoning about how attractive and repulsive forces affect electron transitions, but it appears that she possessed an inaccurate model grounded on electrostatic concepts. Despite her incorrect reasoning, she illustrated some limited conceptual understanding of the absorption and emission phenomena, even though she had a hard time remembering the name for emission.

Her response to another question was also a good indication of her incomplete understanding.

- (Q: In 1802 William Wollaston noted that the appearance of dark lines in the spectrum of sunlight. These lines are due to the presence of certain chemical elements in gases surrounding the sun. Here in the part a we ask you to explain why sharp dark lines appear only at specific wavelengths? So what can you tell us about those dark sharp lines in the sun's spectrum?)
 M1: I kind of like sort of guess on this one. I just said that we are unable to precisely [see] what is happening there may be because of that frequency that we cannot see it. It's something that the human eye is not able to observe and you have to use may be a different kind of lens or something like that to be able to see it.
 I: Okay. So, since we cannot... I mean our...
 M1: Perception of vision

Student M1's response to the question about absorption lines did not reflect the scientifically appropriate explanation. She believed that our visual perception is limited to certain ranges of electromagnetic waves; consequently, we cannot see light at some frequencies outside the visible spectra and instead see sharp dark lines. In her explanation, she did not mention atomic spectra at all. This is possibly an indication of her incomplete conceptual understanding of atomic spectra. Unfortunately, she gave the same reasoning in a similar question on an inter-lesson assessment, even though she revised many of her inaccurate models about atomic spectra after the model-based inquiry lessons.

M1: An excited atom can return to its ground state by absorbing electromagnetic radiation. That's wrong. It has to emit. So, if an electron is on these supposedly three levels [she drew three energy levels] and return this, it would have to emit not absorb. Absorb would go to the next level. So, I said that was false or I just cross off. Umm... the next one, after an atom becomes excited, the electron remains in the excited state indefinitely. Once it gets excited I think it just stays there unless anything else happens. So, third was the energy...

Another indication of her discrete entity model of atomic spectra was revealed with a true/false question. She marked as correct a statement that said, "*After an atom becomes excited, the electron remains in the excited state indefinitely.*" Her answer and explanation of this statement support the claim that Student M1 had a scientifically incorrect understanding about how the absorption and emission processes occur in an atom.

M1: For this one, I said an electron [in the $n=4$ state in the hydrogen atom can go to the $n=2$ state by emitting electromagnetic radiation at the appropriate frequency] yeah so it supposedly on the forth state. This is the fourth state. It cannot go to the second state which is this it can emit. And then it can go there.

I: Is it possible for an electron goes from ... directly from 4 to 2?

M1: No it has to go 3 first. It cannot just like jump.

I: Okay, it should follow the order. Like 4 to 3, 3 to 2, 2 to 1?

M1: Yeah

Student M1's discrete entity quantization model appears to have been affecting her model for electron transitions between energy levels and, ultimately, her model of atomic spectra. In her verbal explanation, she indicated that electrons have to follow an order when emitting photons. This means that electrons cannot transition between multiple levels at once. However, after she completed the model-based inquiry activities, she revised her model of electron transitions to approach the target model. Figure 5.1.5 shows the possible transitions between four energy levels.

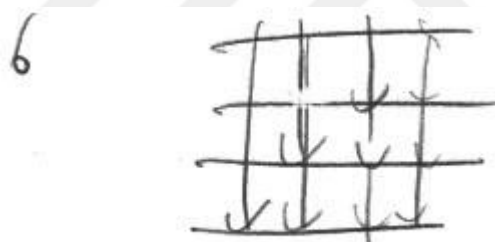


Figure 5.1.5: Student M1's model of electron transitions

To the question, in an inter-lesson assessment, about how absorption and emission occur in an atom, Student M1's response was "*absorption goes to higher level, emission goes to lower.*" Although her explanation was correct, it is very difficult to know from this statement whether she completely comprehended the absorption and emission process. However, her diagram of an absorption spectrum revealed that her model was still not complete (see Figure 5.1.6).



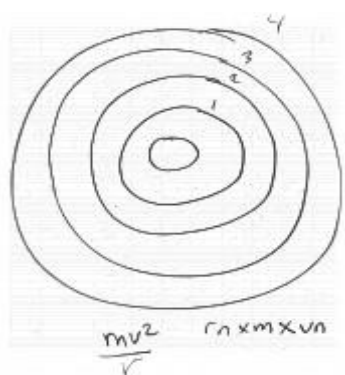
Figure 5.1.6: Student M1's depiction of an absorption spectrum from an inter-lesson assessment

Student M1's sketch of an absorption spectrum consisted of colored lines closer to the long wavelength side and it looked like an emission spectrum. Since she did not complete a post-questionnaire, it is not possible to establish the nature of her final model for atomic spectra.

5.1.4 Lesson 4: Bohr's Model of the Hydrogen Atom

The Bohr atomic model was used by many students, either for easy representational purposes or because they accepted the model as a real representation of an atom. Student M1's initial model of the atom also consisted of many pieces from the Bohr model representation. However, except for the representation, she indicated no further knowledge of Bohr's theory. For instance, in response to a question about different spectral line series, her answer was that she had not heard of them. Unfortunately, she still could not give a complete description of spectral line series in the inter-lesson assessment.

During the model-based inquiry lessons, Student M1 demonstrated a limited understanding of Bohr's assumptions and how to derive the Bohr radius. When we asked the same questions in an inter-lesson assessment, she drew a picture and calculated the Bohr radius using Coulomb force and centripetal force (see Figure 5.1.7).



a) Bohr radius representation

$$\text{Bohr radius} = \frac{kq^2}{r^2} = \frac{mv^2}{r}$$

$$r_n m = \frac{mv^2}{r}$$

$$\frac{kq^2}{r} = mv^2$$

b) Bohr radius mathematical model

Figure 5.1.7: Student M1's representational and mathematical models of Bohr's atomic theory

In Figure 5.1.7a, Student M1 depicted Bohr's radius and his quantized angular momentum assumption. Figure 5.1.7b, on the other hand, presents her attempt to calculate the Bohr radius. She had a good start by using electrical force and centripetal force; however, she could not carry out her calculation to derive r .

Likewise, her understanding of Bohr's assumptions was also still incomplete after she completed the model-based inquiry activities. Her response to an inter-lesson assessment question about Bohr's assumptions was "*Bohr's assumption was that electron move in a circular orbit for the hydrogen model. A hydrogen model has only one electron. This model only works for hydrogen b/c it has 1 electron. It could not work for any other atom that has more than 1 electron.*" Based on her answer, it appears that she only remembered one of the four assumptions. Furthermore, she stated one of Bohr's postulates as the reason that his model was not accepted.

5.2 Evaluation of Student M2's Model

Student M2 was a freshman level physics student during the spring semester of 2016. He took an IB higher-level physics course in Thailand and had enrolled in PHYS2H and CHEM1 prior to the data collection period. At the beginning of the study, he indicated that he had learned “elementary” concepts of quantum mechanics in high school.

Student M2's atomic models before and after intervention are presented in Figure 5.2.1.

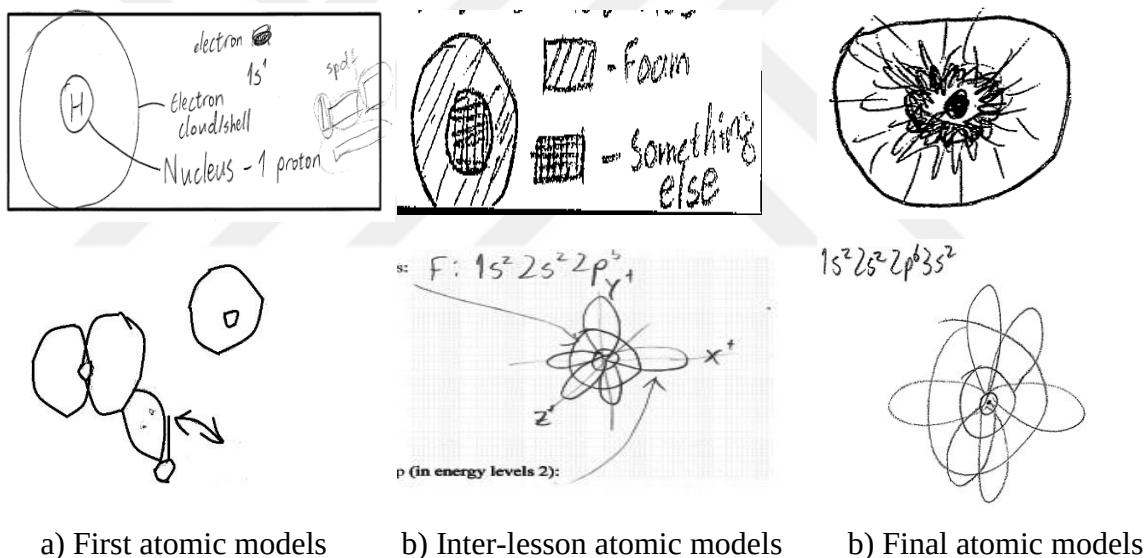


Figure 5.2.1: Student M2's initial, middle, and final atomic models

His initial atomic model is an example of a hybrid model, in which Bohr and orbital models are blended to form a new model. Even though he used the term 1s for the hydrogen atom and had different orbital shapes in his multi-electron atom, he drew electrons at specific locations in the orbitals and used mixed terminology in his explanations. His final models, on the other hand, were the closest to the target (scientific) model out of all the students in the study. For his hydrogen atom, he showed

probability density with black and grey areas. He indicated that the electron is likely to be found closer to the nucleus of the atom. Although he did not talk about probability density in his multi-electron atom model, he drew orbitals and wrote down the related electron arrangement.

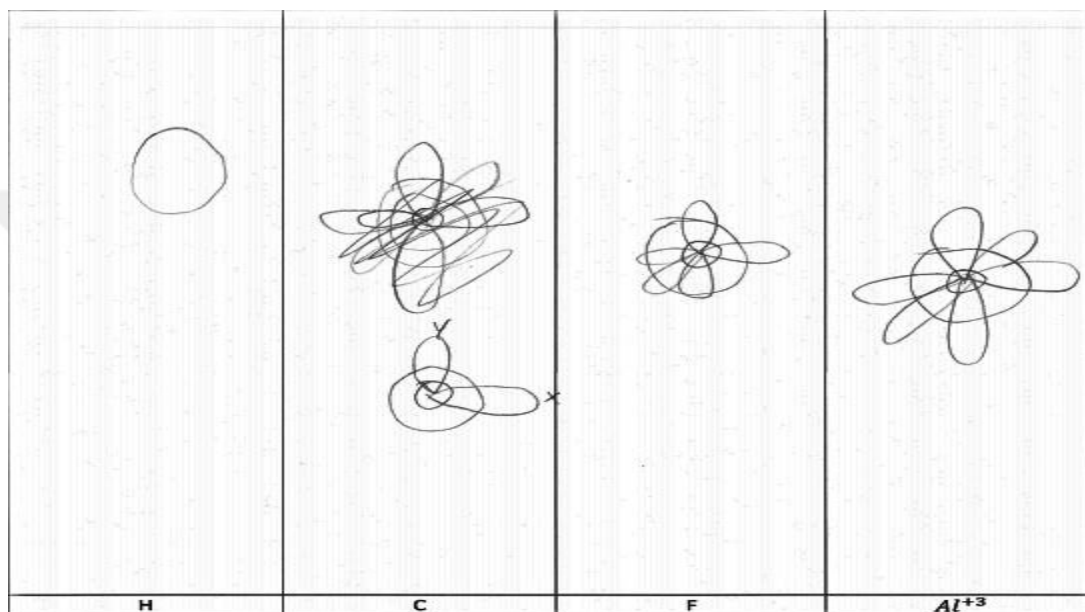


Figure 5.2.2: Student M2's multi-electron atom models as depicted on a worksheet

Figure 5.2.2 demonstrates Student M2's atom models for different elements with different numbers of electrons. He showed orbitals and their shapes although he did not mention or indicate probability density in his models.

5.2.1 Lesson 1: Early Atomic Models

The first lesson about early atomic models consisted of three model-based activities. Student M2's prediction concerning Thomson's plum pudding model activity was *"If it's just foam inside, the skewer will go straight through. If there's something rigid inside, it wouldn't get through."* His logic was fairly straightforward. Based on his observations, he drew a picture of a spherical atomic model (see Figure 5.2.3).

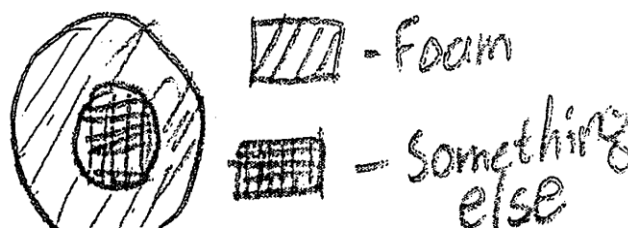


Figure 5.2.3: Student M2's Thomson atom model

Student M2's drawing includes some sort of mass at the center of the spherical foam ball. He must have assumed that there was a nucleus at the center, based on his prior knowledge of early atomic discoveries, as this was not the case for the physical model he examined. After completing the activity, he reported his observation, saying, *"when the skewer goes through the center, it makes different noise compared to when it's going through the edge. Feels like there's hollow space inside, and sometimes it gets stuck –so something else is in it?"* His observational notes after completing a computer-based simulation, on the other hand, were *"In a straight line, energy doesn't change the outcome, at uniform speed... with increased energy, the trace is still a straight line. The density of a particles change?"* The simulation reinforced the idea that when different particles are sent into an atom, most of the particles continue along their trajectories (based on Thomson's theory of atomic structure). It seems that these two different models introduced some conflicting notions to Student M2's existing model and provoked some questions, which led him to revise his model.

For the electron beam cathode ray activity, Student M2's prediction was *"if it is not magnetic nor have charges, it will travel in straight line if it is, it will curve towards magnets."* Although we instructed students to assume that we do not know what the small balls are made from, and that the plates are positively and negatively charged, when he made his prediction he mentioned that the balls might be magnetic or charged

and thus may curve toward the magnets (plates). After making observations, he changed his mind and said, *“they mostly curve and stick to the positive plate.”* He connected this activity with an electron’s motion when it passes between cathode and anode plates, as *“they are negatively charged, so the field created by the plates make them curve towards cathode (oppositely charged), just like how electron would. Also electrons have very small mass, so they will curve more.”* With this statement, he demonstrated a significant understanding of electron behavior in an electric field.

His prediction for the Rutherford atom model showed similarities with his prediction for the Thomson model. After engaging with the physical model, he drew a diagram showing what he imagined the physical model to be like (see Figure 5.2.4).

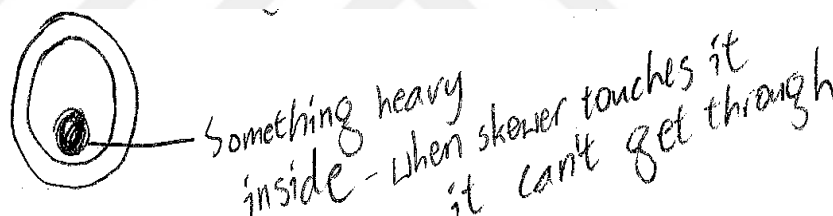


Figure 5.2.4: Student M2's Rutherford atom model

To describe his observations of the physical model, Student M2 stated, *“there’s something dense and heavy in the ball because sometimes the skewer hits something and doesn’t go through, and sometimes it pushes something and then go through, so whatever is inside must be very rigid.”*

His observations from the computer-based simulation were *“ α particles mostly go straight, and some curve at small angles. Most α particles curve, some at very large angle. Lower energy α curves at bigger angle.”* He also described Rutherford’s alpha-particle scattering experiment as follows. *“The α -particles scattered at varying angle depending on their distance from the center of nucleus, thus showing that there’s a dense*

pack of positive charge in the center of an atom.” One of the inter-lesson assessment questions asked what we would expect if Thomson’s plum pudding model was correct. Student M2’s response to that question was *“They should all uniformly go through the foil.”* For the planetary model, he described the simulation with the observation *“The electron orbits around the nucleus, then eventually falls into the nucleus.”*

When asked what the early atom models successfully explained and/or how they failed to explain certain atomic behavior, he responded, *“Plum pudding model was successfully in introducing electrons into atomic theory, but not in explaining the actual structure. Planetary model successfully explained how and why atoms interact with charged particles and demonstrated the existence of nucleus, but fail to explain the stable orbit of electrons.”* In his written answer, he briefly summarized the Thomson and Rutherford models. In an open question, I asked students to think about why electrons and protons were discovered before neutrons. Student M2 responded to that question by saying, *“Because they are charged particles, so it's easier to isolate them or observe how they interact with other particles.”* After he engaged with various model-driven activities, he constructed a coherent and meaningful understanding of the pros and cons of the Thomson and Rutherford models as well as the main outcomes of their experiments.

5.2.2 Lesson 2: Energy Levels and Quantization

Student M2’s initial model of quantization and energy levels fell into the hybrid model category. Like many students, his initial conceptual model of energy transitions was that an excited electron always returns to ground state, no matter what the initial state was. An example from his pre-interview responses is *“... the electron can also emit*

light. Well yeah it can emit photon. So, at some point it would go back to ground state, I think.” His initial energy levels model also gave evidence supporting this initial conceptual understanding. Student M2’s energy level models before and after the intervention are presented in Figure 5.2.5.

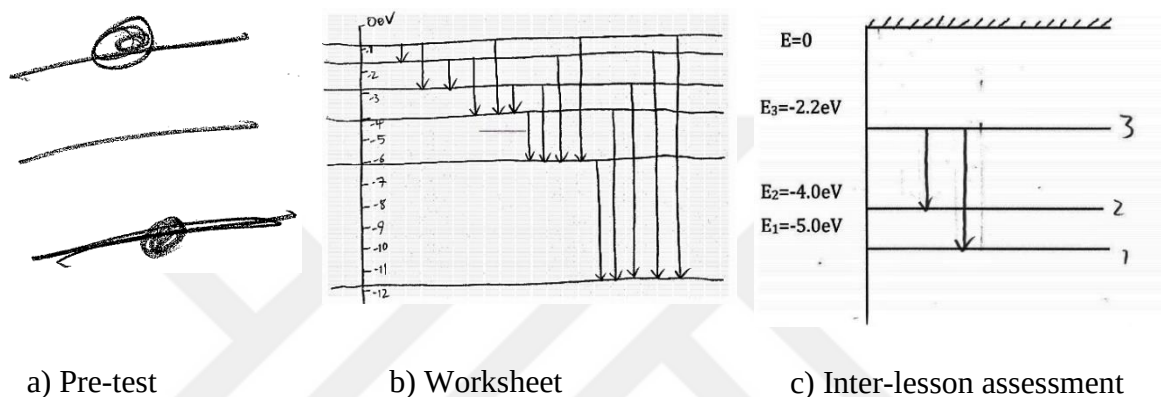


Figure 5.2.5: The evolution in Student M2's energy levels model

He demonstrated a sufficient understanding of how each atom has specific energy quantization and of the relationship between wavelength and the energy required for a photon to be absorbed or released by a specific atom. However, when he was required to explain the relationship between energy and frequency (or wavelength), he showed some deficiencies and inconsistency in his reasoning.

M2: I just said its energy putting discrete units like energy carried by each photon are fixed. I think, because if electron absorbs certain number of photons, then it's the energy carried by photon each photon multiplied by the number of photons. So it's measured in discrete numbers not like a continuous one.

I: Okay. So the quantization of energy is all about the photons. Is that correct?

M2: That's the only example I can think of, but I don't know maybe it could also relate to other particles or other concepts.

I: So, how energy is quantized in a hydrogen atom?

M2: The electron energy levels are fixed.

I: What do you mean by fixed?

M2: So like the $n \dots n=1$ level for example has... and the electron n

equals one level has specific value of energy that it has. And it couldn't absorb... it could only absorb photons in specific wavelength or frequency to move up or emits specific wavelength to move down, but it can't absorb other most other wavelength or emit other wavelength which would then put them in between energy levels because they can't be there. They could only be at specific levels.

I: What is the relationship between energy, wavelength and frequency?

M2: Frequency of light?

I: hmm hmm

M2: Umm... frequency of light is determined by the wavelength because speed of light is constant. So, I have to think. The lower the jump between lower energy levels tends to have bigger gaps in the amount of energy. So, that means the frequency absorbed by an electron in lower energy level is higher. And the wavelength would be shorter and the frequency of light absorbed by an electron higher energy level would be lower. And the wavelength would be greater, I think.

When Student M2 was thinking aloud about the relationship between frequency, wavelength, and energy, he used the energy level diagram from his existing model. However, his statement *"The lower the jump between lower energy levels tend to have bigger gaps in the amount of energy"* indicated his confusion about the amount of energy required for a jump between lower energy levels. However, his reasoning for there being higher frequency photons as a result of transitions between lower energy levels was correct. Later, he was also confused about the relationship between energy, wavelength, and frequency.

I: Okay. So, that means there is an inverse relationship between frequency and wavelength.

M2: Hmm... I guess so.

I: And again inverse relationship between energy and frequency.

M2: Umm... actually maybe it is not inverse. Because, I think it's actually the amount of energy in electron is actually correlated to the frequency. Because umm... so the energy carried by a moving particle, for example is related to the speed of the particle, but then since the speed of light is constant and...

I: You can write if you want.

M2: [He start writing the equations] Because of so the speed of a wave is frequency x wavelength. I think and because speed of light so that's

related to the energy. But then because c is constant we have to just use c/λ or just c is $f\lambda$ and c is related to f . And so because we can't really... because c is constant so we don't... it doesn't really mean anything in this [$v=fc$ equation]. So if we replace that with the frequency and λ , it will be E is $f\lambda$. So, it would be correlated to frequency, I think. I'm kind of get lost... sorry.

I: That's all right.

M2: Okay. Let's see... So, E is related to v [he thinks by himself] ... I do not know I feel like I mean this is what I got [he showed $E \sim f\lambda$ equation], but then I feel like that does not make sense.

I: Why?

M2: Because that means... the energy increases when the frequency increases, but then it also increases when λ increases, which seems weird. Because if the wavelength is greater than... the frequency has to go down, because c is constant. But then in that case that would mean as the... when the frequency goes down, the energy can go higher, when the λ is greater.

I: So, is that mean λ should not be here [By showing $E \sim f\lambda$]?

M2: Probably. So, that should not be λ I guess [he crossed λ in $E \sim f\lambda$ equation]. But I am not sure what would be there.

First, he tried to figure out the relationship between energy, frequency, and wavelength, and he referred to the equation that involves the speed of light, frequency, and wavelength. He wrote the equation correctly but could not interpret how an increase in one of the values would affect the others, even though he said that the speed of light is constant. After poring a little more, he tried to come up with another equation that involved energy, frequency, and wavelength. Based on the new equation, frequency and energy seemed to be inversely proportional. However, the equation conflicted with his initial model; therefore, he could not complete his explanation with satisfactory reasoning. The efforts to give him some clues to help him recall the correct mathematical formula turned out to be useless as his prior knowledge of these concepts was limited.

I: Do you know anything about Planck constant?

M2: Is the h thing?

I: Hmm hmm

M2: I know what it is, but I don't know how I could put it in this question.

I: Do you know anything about de Broglie Equation? Wave equation?

M2: Wave equation? Is it the... I think I know what it is but cannot remember exactly what it looks like. It did have that [h] and frequency and c in it I think...? Either c or λ . I cannot remember which one it is. And it was like something multiplied by something over something equals energy. It looks something like that, but cannot remember what goes in each place.

After completing the model-based activities, Student M2 stated, “*Energy of photon is proportional to the frequency, so blue light has more energy $E=hc/\lambda$, $c=f\lambda$, $E=hc/cf \therefore E=hf$,*” in response to a question about whether blue or red light in a rainbow has more energy. He supported his argument with a mathematical formula and derived equations to show the relationships between frequency, wavelength and energy.

5.2.3 Lesson 3: Atomic Line Spectra and Energy Levels

Student M2's model of atomic structure included some inconsistencies prior to the study. The growth in his understanding of quantization seemed to allow him to individually develop a meaningful model about the absorption and emission process.

(Q: In 1802 William Wollaston noted that the appearance of dark lines in the spectrum of sunlight. These lines are due to the presence of certain chemical elements in gases surrounding the sun. Explain why sharp dark lines appear only at specific wavelengths.)

M2: So the electrons in the elements or the atoms can only absorb very specific wavelength of light. So if there is those elements in the sun's... the gases around the sun then those light would be absorbed by the gas the electrons in the Gas atoms. So those lights would be missing.

(Q: How a comparison between the spectrum of sunlight with the dark lines and the spectrum of light from a sodium lamp can identify that sodium is one of the elements in the Sun's atmosphere?)

M2: Because all elements have like different compositions, size and stuff like that, I think the energy levels of each element are unique, I think. There shouldn't be overlaps I think. So, if we can see the same lines missing then we could say that there is probably the same elements in both places.

I: So, is that mean that the same photon with the same wavelength can be absorbed by a helium atom as well?

M2: Umm... probably not, because helium atom would have different energy levels. So they would [be] different... they would absorb light at different wavelength. So, the light with the wavelength that sodium can absorb would probably just get through without being absorbed.

Student M2's responses to these two questions reflected a comprehensive understanding and transfer of knowledge concerning the energy levels of different elements and their absorption spectra. Although his photon emission model seemed to be incomplete, his explanations of the emission process contained the general principles of the whole idea.

M2: And... because it's moving from higher energy level to lower energy level. And it happens by emitting light.

...

I: Is it possible for an electron to go from 4 to 3 and 3 to 2? Or should it go from 4 to 1 directly? Or it can jump like this between any stages?

M2: I think it really matters. Because it could either emit two photos with different wavelength corresponding to 4 to 3 and 3 to 2 or you can have one photon that has all the energy difference in between those. And because light can carry as much energy as it would like to have. I mean there's like no limit in the light spectrum. So, I don't think that matters.

The response that Student M2 gave to this particular question demonstrated that he understood the ideas of emission and electron transitions between different energy levels. However, in response to the previous question, he stated that electrons go directly back to the ground state.

M2: ...because the electron can also emit light. Well yeah it can emit photon. So, at some point it would go back to ground state, I think.

These two answers showed that M2's model of emission consisted of some mixed information. Additionally, his initial model indicated that emission does not follow absorption. These two phenomena occur independently of each other.

I: So, how long do you think an electron stay in excited states?

M2: Umm... I am not really sure.

I: And what is the determination of that time period for an electron stays in an excited state?

M2: Umm... Maybe it's random like nuclear decay. I'm not really sure how long it would take. Maybe it's instance, maybe it can take like a lot of time.

After completing the atomic spectra lesson, the students took an inter-lesson assignment. In response to one item, which asked what emission and absorption are, Student M2 said, *"Electrons absorb or emit light at fixed frequencies in order to move between different energy levels."* He was also able to show all the possible transitions between given energy levels (see Figure 5.2.6) as well as spectra for the absorption and emission processes (see Figure 5.2.7).

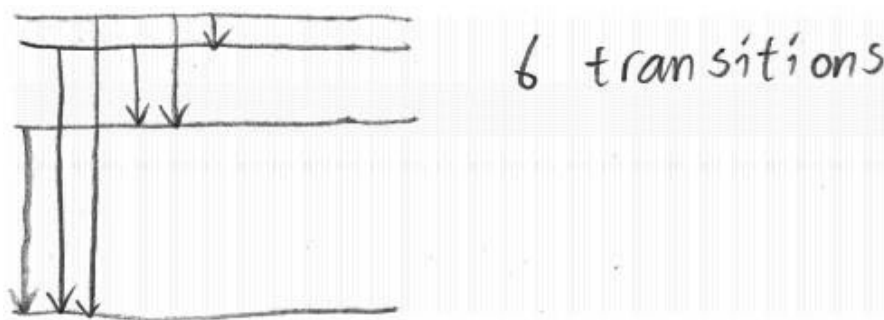


Figure 5.2.6: Student M2's depiction of electron transitions during the emission process



Figure 5.2.7: Student M2's depiction of atomic spectra

In Figure 5.2.6, the student showed six possible transitions between four energy levels during the emission process. In this depiction, he confirmed that any transition between any two levels is possible. Figure 5.2.7a presents the students' drawing of an absorption spectrum and Figure 5.2.7b shows his emission spectrum depiction. Since we asked the students to roughly sketch the absorption and emission spectra, we were not expecting a precise depiction of any element's spectrum. In the post-questionnaire, Student M2 was able to select the correct transitional lines corresponding to a given emission spectrum out of similar energy level diagrams (see Figure 5.2.8).

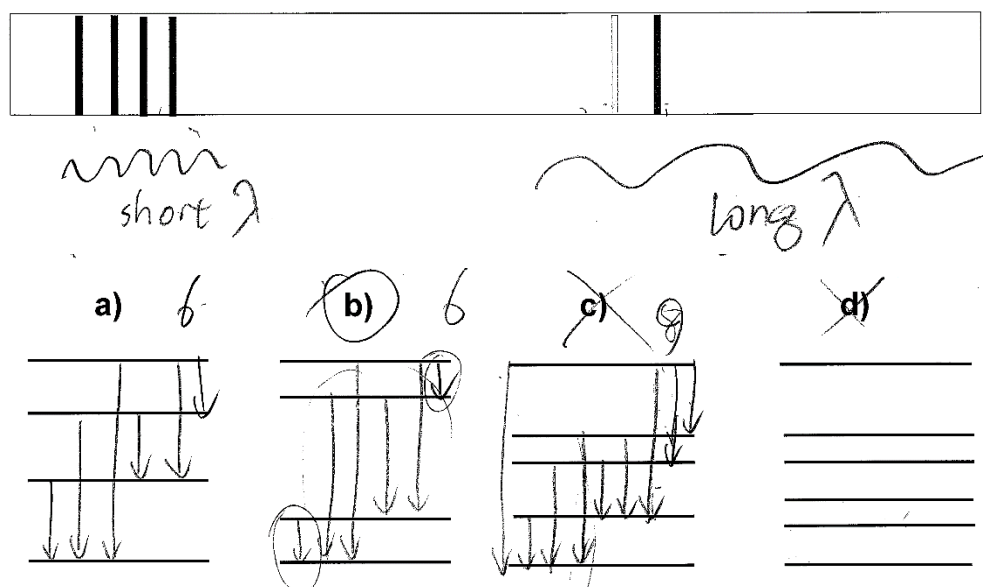


Figure 5.2.8: Student M2's post-questionnaire response concerning electron transitions in the emission process

His reasoning in his process of elimination indicated that his model of atomic spectra had reached the target scientific model.

M2: I chose b. Because first of all on the emission spectrum there's six spectrum lines. And only a and b have six spectral lines and c and d has too many. And out of those... so on the spectrum, there're four lights... four visible lights with short wavelength and two with long wavelength. And b shows two very short ... very small level energy transition and four large level transition which means it emits... and so the less energy there is, the longer the wavelength it gets. Because it's inversely related to the wavelength... the energy I mean. So, the shorter... two shorter wavelengths would lead to two long wavelengths of light and four long... four large energy transition would lead to four short wavelengths.

In his explanation, he mentioned the relationship between the number of energy levels and the number of spectral lines observed in the spectrum. Furthermore, he talked about how the distance between energy levels dictates the wavelength of emitted light (the photon), and therefore also its energy and frequency.

5.2.4 Lesson 4: Bohr's Model of the Hydrogen Atom

Student M2 did not explicitly refer to the Bohr atomic model when he described atomic structure or quantization and atomic spectra in the pre-questionnaire. However, the Bohr model and Bohr's assumptions were hidden components of some of Student M2's initial models. Furthermore, he showed hardly any knowledge, or a very limited understanding of the Balmer and Lyman series. Transcribed below are excerpts from the pre-interview with Student M2 about spectral line series.

I: Have you heard anything about Lyman series, Paschen series?

M2: I think I did hear about it, but I don't remember which one is which. I know it's related to the absorption and emission spectrum thing. The energy levels... but I don't know which one corresponds to which one. So, I leave those out for now.

Based on students' answers and our discussions during the implementation of the study, most students indicated that they were familiar with the Bohr atomic model representation, but their knowledge of Bohr's assumptions and of how he proposed his theory were at a very superficial level. In other words, they had heard of Bohr's quantized energy levels and of electron stability at specific energy levels without understanding the underlying reasons for these ideas. After Lesson 4 was completed, Student M2 stated, "*He assumed that the lowest energy level is stable and so it will not collapse*" in response to a question about Bohr's explanation for what keeps electrons from striking the nucleus. His statement was not supported with any other reasoning; therefore, it is hard to infer why he thought that only the lowest energy level is stable.

During the lesson, students were asked to derive the Bohr radius formula by using related equations concerning electron circular motion. In the inter-lesson assignment, one question asked students to write an expression for the radius of the n^{th} orbit in hydrogen-like atoms and to draw a graph showing the relationship between the radius of the orbit and the energy level of electrons in a hydrogen atom. This question aimed to find out if students could transfer their understanding of related entities or phenomena. Student M2's mathematical and graphical models of the relationship between Bohr radius and the energy required at each energy level is shown in Figure 5.2.9.

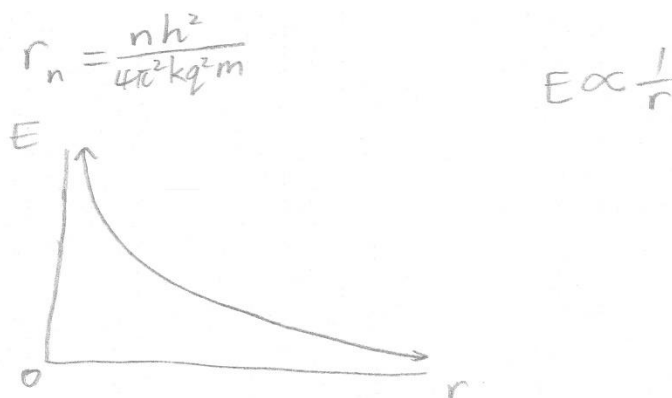


Figure 5.2.9: Student M2's mathematical and graphical models of the relationship between Bohr radius & energy level

Although we did not talk about the energy/radius or energy/ n^{th} energy level relationships during the implementation, Student M2 was able to apply his mathematical model to explore these. He showed a strong conceptual understanding of the relationship between energy and radius; but, for some reason he did not consider the negative energy idea in his graphical representation. His graphical model consists of the classical energy/distance relationship. He assumed that the energy (potential energy) is positive and decreases exponentially as the electron moves further away from the nucleus.

In the post-questionnaire, Student M2 stated the assumptions that Bohr made when he proposed his theory and categorized them according to classical physics, quantum physics, or a mixture of the two. He demonstrated sufficient understanding to distinguish between classical and quantum mechanics ideas, even though he could not remember all four assumptions correctly. However, he was able to explain all four spectral series of emission lines (the Balmer, Lyman, Paschen, and Brackett series) and to calculate wavelengths to identify which one was in the visible range of the spectrum.

5.2.5 Lesson 5: Wave Mechanics and the Hydrogen Atom (Quantum Mechanical Hydrogen Atom)

Student M2's initial atom model consisted of some elements from the quantum mechanical view of the atom. He talked about orbitals and quantum numbers but his knowledge of quantum numbers and electron arrangements, which was determined in the pre-questionnaire, indicated that he had an incomplete model of the quantum mechanical hydrogen atom to start with. Below is a quotation from the pre-interview with Student M2. The question asked him to match four quantum numbers with their proper definitions.

M2: I feel like that should be spin [describing the direction of the electron's angular momentum], because it is to do with angular momentum. And I presume they named it spin because it is to do with like angular momentum. So, that rules those two out [E and F]. Umm... I feel like that should be D [describing the orientation in space of a particular orbital], because the magnetic fields of moving charges are related to the orientation of the motion. So I feel like that would be related to the magnetic quantum number. Okay, I will just cross this one. So, then the only other thing that's related to the orbital is principle. So I guess that's what is it [describing the size of the orbital].

His response showed that although he could not remember the four quantum numbers precisely, he was able to match the correct quantum numbers with their descriptions by process of elimination. Figure 5.2.10 presents how Student M2 calculated specific electrons' quantum numbers after the model-based inquiry activities.

The 4 th energy level has 4 sublevels called:	- 4f, has 7 orbitals called 4f and can have 14 e⁻ - 3d, 5 orbitals, 10e⁻ - 2p, 3 orbitals, 6e⁻ - 1s, 1 orbital, 2e⁻	16	32
The 3 rd energy level has 3 sublevels called:	- 3d, 5 orbitals, 10e⁻ - 2p, 3 orbitals, 6e⁻ - 1s, 1 orbital, 2e⁻	9	18
The 2 nd energy level has 2 sublevels called:	- 2p, 3 orbitals, 6e⁻ - 1s, 1 orbital, 2e⁻	4	8
The 1 st energy level has 1 sublevel called:	- 1s, has 1 orbital and can have 2e ⁻	1	2

Figure 5.2.10: Student M2's orbitals & number of electrons calculation table

After making observations with a de Broglie model simulation, which demonstrated a hydrogen atom being exposed to monochromatic light, he said, “*When light with wavelength that doesn't match with the energy level is used, there is no change in energy (no absorption/ emission). But for certain wavelength of light, it gets absorbed and randomly emits one of the possible wavelength of light, until the electron is stable.*” Later, Student M2 engaged with the Schrödinger model simulation and recorded his observations, writing, “*it seems that the quantum number increases, as it can be seen that the s orbital transforms into a p orbital or higher due to the electron having higher energy.*” In this statement, he explained how absorption and emission occur. At the end of the activity, his explanation became more sophisticated and scientifically appropriate. He mentioned the changes in quantum numbers when electrons jump to higher energy levels, as well as how electrons may occupy different orbitals. Later, Student M2 showed the relationships between frequency, energy, and wavelength and derived the time-dependent Schrödinger equation for one spatial dimension (see Figure 5.2.11).

$$\begin{aligned}
 & KE = \frac{p^2}{2m} \quad E = KE + PE, \quad KE = \frac{1}{2}mv^2 = \frac{p^2}{2m}, \quad p = \frac{h}{\lambda} \\
 & \psi(x) = Ae^{i(kx - \omega t)} \\
 & \psi'(x) = Ake^{i(kx - \omega t)} \\
 & \psi''(x) = -Ak^2e^{i(kx - \omega t)} = -k^2\psi(x), \quad k = \frac{2\pi}{\lambda} \\
 & \psi''(x) = -\frac{p^2}{h^2}\psi(x) \\
 & h^2\psi''(x) = -p^2\psi(x) \quad \psi(x)E = \frac{p^2\psi(x)}{2m} \neq V\psi(x) \\
 & E\psi(x) = -\frac{h^2\psi''(x)}{2m} + V\psi(x)
 \end{aligned}$$

Figure 5.2.11: Student M2's derivation of Schrödinger's equation

After the model-based inquiry activities, in response to a question that asked for a description of Schrödinger's equation, Student M2 answered, "*the possible location of the electron in an atom.*" In response to another question that asked about wave function, he responded, "*A function to describe the electron wave.*" Moreover, he explained the difference between Bohr's model and the currently accepted atomic theory, saying, "*the electron is not a particle at all times and it does not follow a circular orbit.*" Although he improved his conceptual understanding of fundamental quantum concepts, his written responses still showed some incomplete ideas. The following text was excerpted from Student M2's post-interview responses.

I: What is "l" describes?

M2: That's the orbital quantum number and it determines the shape of the orbit. And the ml which is the magnetic momentum, it goes from +l and -l and the spins just up and down which is plus and minus half. And so for each n... sort of like for example if there is four 'n's then there can be three 'l's and which means there can be up to +3 or -3 'ml's and there's two electrons for each one of those which... and from that we can find the combinations of all the possible orbitals that can be formed for n=4 for example. And then we just figure out how many electrons can fit in there.

I: So, for example $n=1$?

M2: If it is $n=1$ then it can only have... $l=0$ which means m_l is also 0. So you can have only two electrons.

I: How about $n=2$?

M2: If it is $n=2$, then it can have the one just mentioned with just one orbital with three electrons. And it can also have $n=1$ which would have one m_l ... m_l is that are 1, 0, and -1 with two electrons in each which means there can be up to six.

I: Okay. What is orbital, shell and subshell mean?

M2: So, the orbital shell is the complete shape that's determined by " l " and subshell is the small section of the shell that contains the pair of electrons.

I: Hmm hmm how about shell?

M2: Shell is when you put all the subshells together, I think

...

I: Okay. What is quantum mechanics? What do you know about Schrödinger equation, wave function, and probability density?

M2: So, quantum mechanics is the description of ... basically way of doing physics with quantized particles and structures which means it takes a very specific state or values rather than a continuous spectrum of them. And Schrodinger's equation is the equation that uses the energy equation the one that has like the kinetic and the total energy equals kinetic energy plus potential energy, and then uses that to describe the electron's energy I think. And the wave function is the function that's used to determine the position of ... to describe the probability density of the electron and the probability density is the distribution of the probability of where we may be able to find the electron.

In the post-questionnaire, he indicated a strong conceptual understanding of quantum numbers and electron arrangements. Although his definitions of shells and subshells as well as his notion of orbitals were not completely scientific or correct, he was one of the students who was able to distinguish between these. Furthermore, his definitions of quantum mechanics, Schrödinger's equation, wave function, and probability density were at a quantum theory level of understanding of atom and electron behavior.

5.2.6 Lesson 6: Multi-Electron Atom

Figure 5.2.12 shows Student M2's models of electron arrangement and orbital notation as represented in the pre-questionnaire, worksheet, inter-lesson assessment, and post-questionnaire.

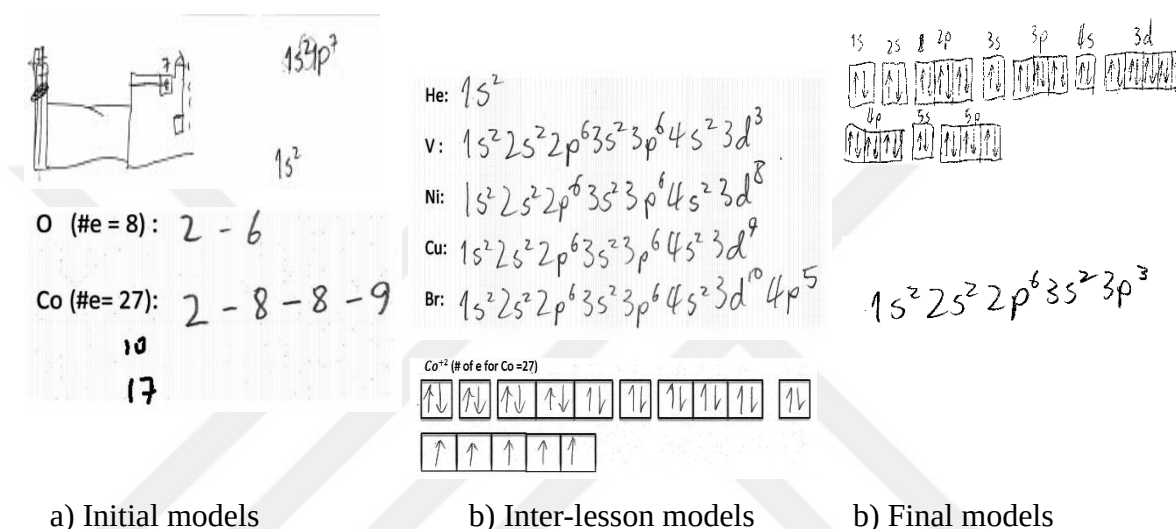


Figure 5.2.12: The evolution in Student M2's electron configuration and orbital notation models

Student M2's models of electron arrangement and orbital notation showed some progression from the beginning to the end of the intervention. However, although his depictions of both models were correct in the worksheet and inter-lesson assessment, he mixed these two models when he was answering the post-questionnaire.

M2: Yeah, I am not sure if I actually finished, because I was counting and then I had to stop. So it fills up from 1s and the... it has one pair of electrons and then 2s which also has one pair of electron and then it goes to 2p which has 6 electrons and then 3s and 3p. And then because 4s has $n+1$ value of 4, 3d has $n+1$ value of 5. So 4s has lower energy than 3d. So, it gets filled up first and then we fill up 3d which has 5 pairs of electron. And then we fill up 4p. And 4p also has... 4p's $n+1$ value is also 5, but then 3d has the n value of 3 which is smaller than 4 so it comes before 4p. And then after we fill 4p we move on to 5s and then after we move on to 5d and so on.

I: Hmm hmm...

M2: Yeah, I don't know if this is actually complete shell but yeah.

I: How about orbital notations?

M2: For Phosphor, the orbital notation I think was $1s^2 2s^2 2p^6 3s^2$ and $3p^3$, I think. I need to check very quickly. Yeah

He applied Hund's rule, the Aufbau principle, and the Pauli exclusion principle in his models. After the model-based activities, his observation, recorded on the worksheet, was *"Each state can only take limited number of electrons. If the lower states are occupied, other electrons must take up higher energy levels."* His reasoning in both his recorded observations and his post-questionnaire interview showed a sufficient understanding based on quantum theory. Except for mixing the two ways of representing electron arrangement, his explanations indicated that he had improved his conceptual understanding toward the expert level.

As part of another activity, he drew s and p orbitals with all their components.

Figure 5.2.13 presents his depictions of the s and p orbitals on his worksheet.

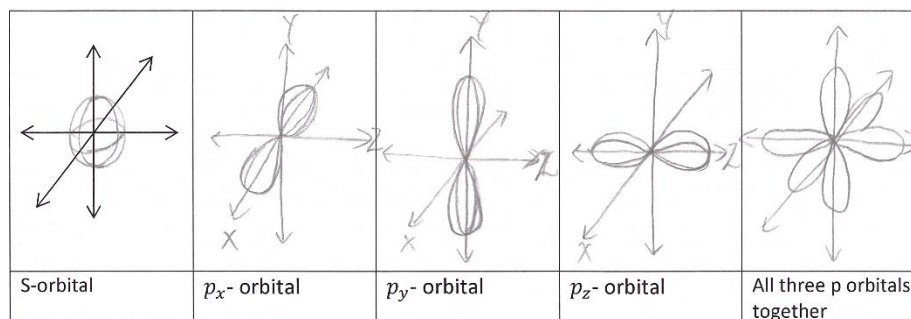


Figure 5.2.13: Student M2's depictions of s and p orbitals

In none of his orbital models was there any indication of probability density or electron attributions. However, in his final model of the atom, he demonstrated the possible areas where an electron could be found in an atom (see Figure 5.2.14).

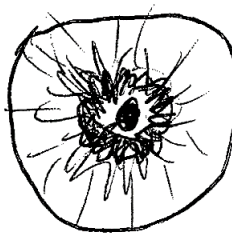


Figure 5.2.14: Student M2's hydrogen atom model

Transcribed below are excerpts from the post-interview with Student M2 about his hydrogen atom depiction.

I: Okay. So, if I want you to draw a hydrogen atom, how would you draw it here?

M2: There would be like the nucleus with the orbital of electron where the orbital has different probability at different place in the orbital where the electron may be there. We cannot tell for sure where the electron exactly is.

I: So, what is that different probability location in different place? What do you mean by that?

M2: So, for example, it is not going to be in the nucleus. But it will be around close to the nucleus, because it is where like the attraction is strongest. It is very... it is more likely to be around the nucleus. And the further we go away from the nucleus the probability of the electron being there gets less and less. And then after a point it is very low that we don't think about that area. And also the distribution of the probability can be described by the wave function of the electron.

In this part of his explanation, he mentioned probability density and wave function even though he was neither asked to explain these two concepts nor were they even mentioned in the question at all. In his multi-electron atom model, on the other hand, he did not include these concepts. This was either because he focused on explaining different orbitals and their shapes, so he lost sight of that component of the atom, or because his model of probability density and wave function was incomplete.

M2: So, there's a black dot which is the nucleus. It would be a lot smaller on scale, but I just wanted to show that it is still there. And around the nucleus there are three different s shells and the smallest which is inside. Two and three is the 1s and it contains... it goes ... contains

around the nucleus. And 2s also surrounds 1s and 3s surrounds 2s and 1s and the nucleus. And it also has the p orbitals. Because it contains 2p⁶ which means it got to full 2p orbital. So it got to 6 subshells in sticking of it different directions

I: Okay six subshells.

M2: Are there six?

I: What are the subshells here?

M2: Umm... six subshells of the 2p. 2p orbital I mean. So, there is one... there is two in the x-axis, two in the y-axis and two in the z-axis. And of course there is also 1s, 2s and 3s. So there is actually more than 6. But just for the p orbitals there is six p orbital subshells.

I: Okay. So, 2p orbital is kind of like 3s here?

M2: It sort of overlaps I think. The shape overlaps but obviously electron would not overlap... take the same space at the same time.

When Student M2 explained his multi-electron atom, he indicated three different s orbitals and their relative sizes. However, he used shells and orbitals terms interchangeably, although he defined orbitals and shells correctly one of his previous answer. Moreover, he said 2p orbital has six subshells presumably by referring the maximum number of electrons in p orbitals. Student M2's response to his question demonstrate his accurate understanding about orbital representation, but incoherent use of terminology.

5.3 Evaluation of Student M3's Model

Student M3 was a freshman electrical engineering student in the spring semester of 2016. She took an IB higher-level physics course in high school and enrolled in PHYS1 and PHYS2 in two consecutive semesters at college and passed the courses. She was working as an undergraduate teaching assistant (UTA) during the period of data collection.

Student M3's atom models before and after the intervention are presented in Figure 5.3.1.

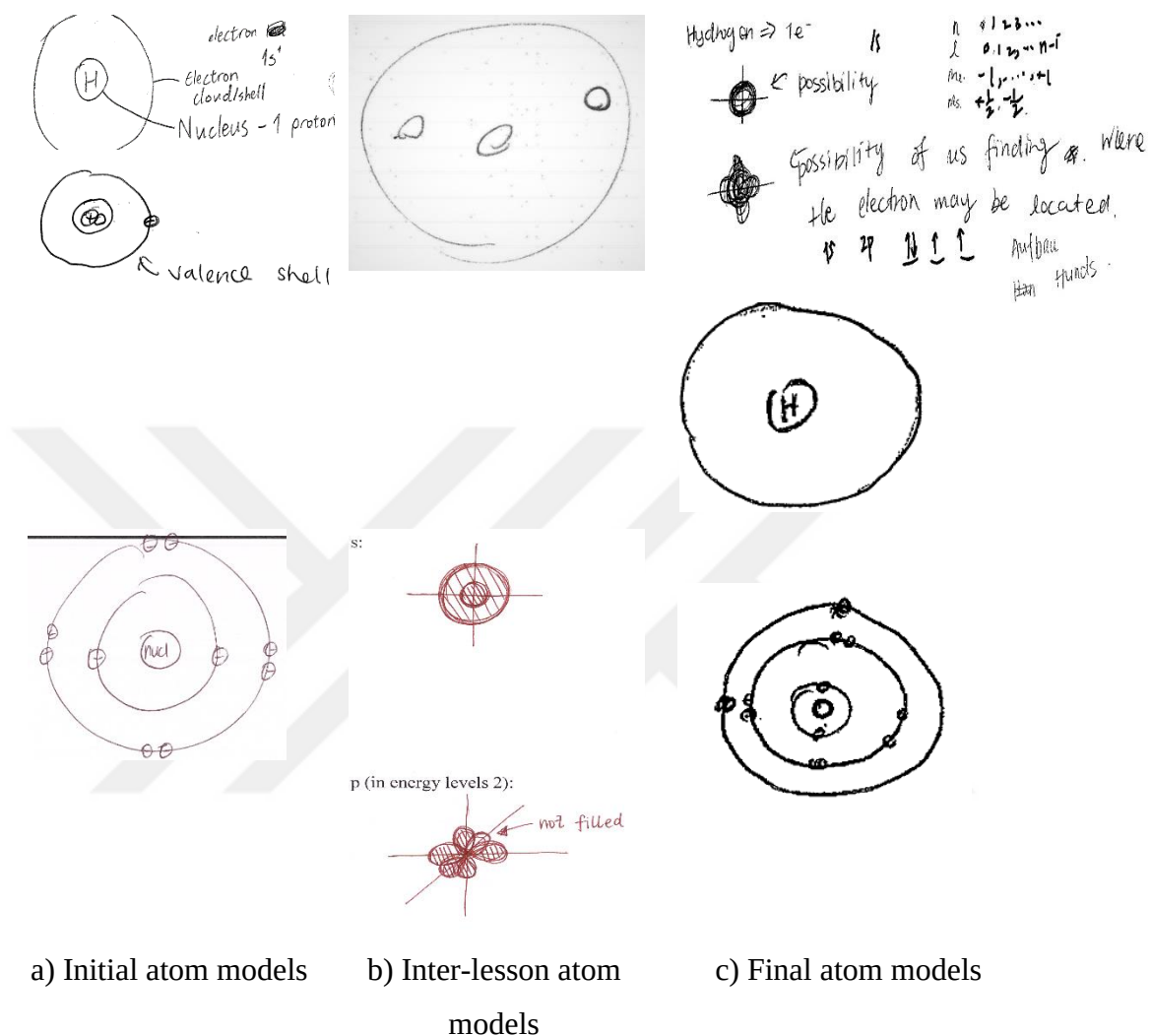


Figure 5.3.1: Student M3's atom models

Student M3 was using a hybrid atomic model prior to the intervention. Her first depiction of a hydrogen atom looks like a 1s orbital although she called the spherical area an “electron cloud/shell.” Her second drawing in the pre-questionnaire looks like a planetary model in which the electron is in a fixed location. However, her multi-electron atom indicated that she had a valence shell model in mind, with electrons approximately located per Lewis dot representation.

After the intervention, Student M3 revised her hydrogen atom model and drew an s orbital. However, she kept the same multi-electron atom model throughout the intervention and drew valence shells to represent the electrons' locations even though she drew s and p orbitals on a three-axis coordinate system in response to the question asking for electron arrangement based on the quantum mechanics model. This pattern in her models shows that she could not construct a sturdy model for a multi-electron atom.

5.3.1 Lesson 1: Early Atomic Models

As displayed in Figure 5.3.1b, Student M3's Thomson and Rutherford models show how she imagined the insides of the atoms. Before the first activity (Thomson model), she said, *"Most skewers should pass completely through the ball with no resistance."* Her prediction indicates that she grounded her idea on what she had experienced with a foam object. After she finished her observations, she reported, *"Most times, the skewers passed through the ball with little resistance. On three occasions, the skewer was stopped by something at a specific distance from the surface."* As result of the observation, she drew an atom that consisted of two electrons randomly placed in a spherical area.

Student M3's engagement with the simulation gave her another insight about the Thomson model. On her worksheet, she recorded, *"the alpha particles are passing through the atom with no loss of energy,"* and, *"[after increasing the alpha particles' energy] The trace remains straight. The alpha particles are slightly faster."*

In another activity, Student M3 was shown a ramp, small spherical objects, and positively and negatively charged plates located on opposite sides of the end of the ramp. She was asked what would happen if the balls were released at the top of the

ramp. Her prediction for this setup was *“The balls should continue along a straight path until it is stopped. If the balls are not magnetized the director of the path should not change.”* It is possible that the student used the phrase “magnetized balls” in her prediction to refer to electrical charges, although we did not tell the students that the balls were magnetized. Later, when Student M3 completed her observations with the balls and the ramp, she drew a model of the “ball’s path” (see Figure 5.3.2) and explained her observations, saying, *“The path of the balls generally drifted toward the positive side. All of the balls were attracted to it and eventually stuck to it.”* When we asked her to explain how this activity informs us about electrons themselves and their path when they pass between anode and cathode plates, she said, *“the motion of electrons would be similar and their path would drift toward positive plate. This is due to their negative charge.”*

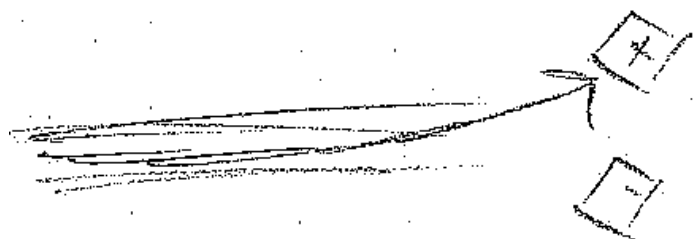


Figure 5.3.2: Student M3's model of the ball's path

Figure 5.3.2 shows Student M3's drawing in support of her explanation of the relation of cathode rays to the activity. Before the observations, she mentioned balls and magnetization to express her prediction about the path of the small beads. However, after making observations and connections to the cathode ray experiment, she started using more accurate terminology such as “positive plate” and “negative charges” instead of magnetization. In response to an inter-lesson assessment question about the repulsion

of a glowing beam by a negatively charged plate, Student M3 answered, *“Glowing beam is repelled by negatively charged plate only because beam itself is negatively charged.”* Her explanation in this question also demonstrates that she was able make connections between the physical model and the cathode ray experiments by matching light beams with “small balls.”

Student M3’s prediction for the Rutherford atom model was similar to her prediction for the Thomson model. While she said, *“Most of the skewers should pass through the ball,”* before the observation, she changed her mind, saying, *“Most of the inside is empty space, except for a small central object,”* after engaging with physical model. With this observation, she started to think about the idea of a nucleus. Figure 5.3.3 shows Student M3’s model of Rutherford’s atom based on her observation of the physical model.

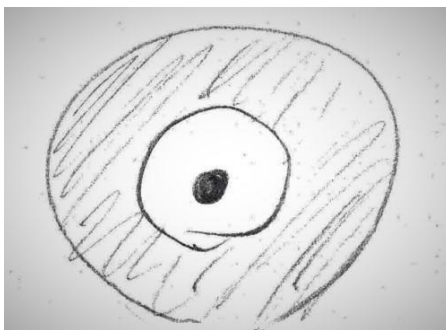


Figure 5.3.3: Student M3’s model of the Rutherford atom

Her model of Rutherford’s atom indicates that there is a nucleus at the center of an empty space. The rest must be the area where electrons are located. Student M3’s observations from the Rutherford scattering simulation were *“1. Only a few alpha particles (those that have the closest approach) are deflected* [when the number of protons and the number neutrons are both 20]. *2. More alpha particles are deflected at*

greater distance and angles [when the number of neutrons is kept the same but the number of protons is increased]. 3. *The deflection of alpha particles is the same as in 1* [when keeping the number of protons, the same but increasing the number of neutrons]. 4. *The deflection of alpha particles is similar to what was seen in 2* [when both the protons and neutrons are increased in number]. 5. *The angle of the trace decreases with higher energy.*” In an inter-lesson assessment, we asked Student M3 to explain the assertions of the Rutherford experiment. Her answer was “*Since alpha particles’ trajectory was affected something must have blocked/exerted a force on it. Must be a positively charged thing to repel alpha particles and deflect them. This charged center is not everywhere b/c some alpha particles deflected very little while others greater (Force is different based on location).*” Another question in the inter-lesson assessment asked what would happen when you bombarded atoms with alpha particles if the Thomson model was correct. Student M3’s response was “*Alpha particles should have gone straight through without having its original trajectory changed.*” Her answers to both questions illustrate that her observations using the simulation helped her to make a connection between the size of the nucleus (number of protons) and the deflection of alpha particles, which are positively charged. She also realized that when alpha particles pass closer to the nucleus, they are exposed to a greater force and are deflected at a greater angle.

Unfortunately, Student M3’s observational note after engaging with the planetary model simulation was not well enough elaborated to know if she understood why the planetary model was not accepted.

5.3.2 Lesson 2: Energy Levels and Quantization

Initially, Student M3 presented models of emission and absorption spectra according to a discrete entity (particle) model. She confused transitional lines with atomic spectra. After she drew an energy level diagram, I asked her to elaborate upon her answer.

M3: But this one [Figure 5.3.4a] like it supposed to get smaller and smaller and smaller.

I: When it gets away from nucleus or when it is closer to the nucleus?

M3: Is this like the atomic spectrum? Or?

I: I don't know you drew it

M3: I just remember that but I don't really remember what it is. So, let's see. If it is closer...Ok, I think for here [Figure 5.3.4a bottom] it is closer to the nucleus and from here [Figure 5.3.4a top] it is farther away, because this one [she showed the distance between the first and second energy levels] has a lot of energy and if it is closer to the nucleus it would need a lot of energy. Versus one is far need less energy

Student M3's verbal explanation demonstrated her confusion about spectral lines and the energy level lines that she drew. First, she asked if those lines were an atomic spectrum and then she started to reason based on her prior knowledge and drawing. Her reasoning indicated that she made a connection between the distance of an energy level from the nucleus and the amount of energy that "it" needs. It is not easy to infer what she referred to as "it."

Student M3's energy levels model, on the other hand, was in the hybrid model category. She had a pretty solid understanding of the atomic absorption and emission processes. She stated that an electron cannot stay in the excited state—it wants to go back to ground state—but she could not explain why. She said, *"After an atom becomes excited, the electron remains in the excited state. Actually this is false because I feel like I remember from physics 1 that it would always like try to return to the ground state. I*

don't know why though." When the interviewer asked her to elaborate on her answer, Student M3 said, *"I don't know but if I have to guess I think it is because that is the most desired state since that required at least energy to stay in. So, then after it becomes excited it will try to always go back to the one that is sort of state the most comfortable in. And that's how it won't stay in excited state indefinitely."* Based on her guess, the electrons want to be in their "most desired state" where they are most stable, and ground state is always the most desirable state. This model was seen among many students.

Student M3's energy levels models before, during, and after the intervention are presented in Figure 5.3.4.

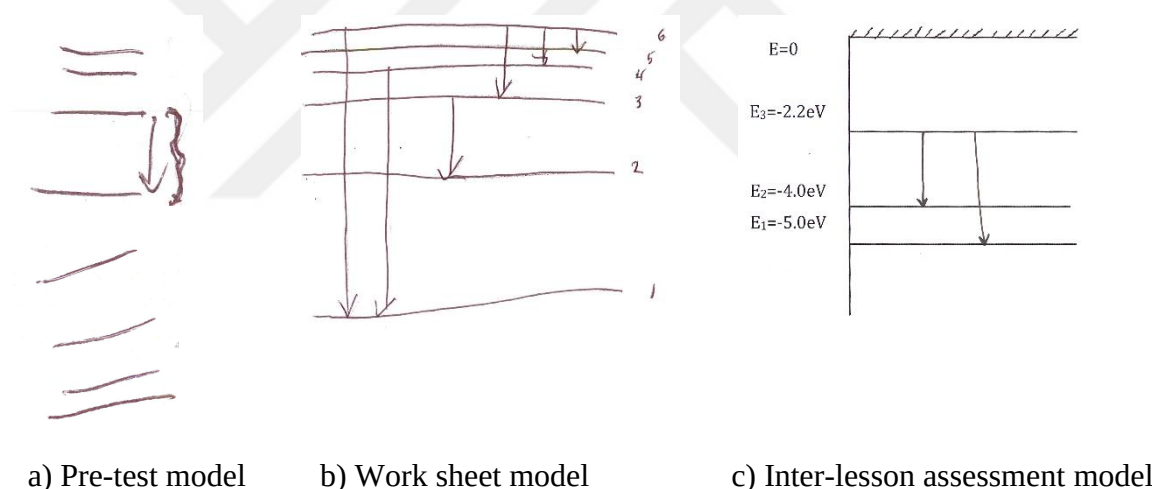


Figure 5.3.4: Evaluation of Student M3's energy levels models

Student M3 did not show transition arrows in her initial model of energy levels. Although it is not clear in her drawing, she said that the distance between energy levels gets smaller as they get closer to the nucleus. In her verbal explanation, she indicated that she was not sure how energy levels should be drawn. She said, *"I don't remember exactly like I know one of them is like this* [she showed her drawing of energy levels reproduced in Figure 5.3.4a, top] *and the other one is like the other way around* [she

drew another energy level configuration below the first one, presented in Figure 5.3.4a, bottom]. *And then one is the atomic one and the other one is the different one. But I don't exactly remember which one is which.*" She believed that there are at least two different energy level diagrams. She called one of them "atomic" and referred to the other one as "different." When she was asked to explain the relationship between energy and frequency (or wavelength), she recalled her prior knowledge using equations.

M3: I know energy and frequency is related this way [she wrote $E=hf$]

I: That means they have what kind of relationship?

M3: Directly proportional. And then energy and wavelength are inversely proportional.

I: How do you know that equation? Have you just memorized it?

M3: Oh, for this one I know this [the equation]. But the frequency and wavelength, you just think about it. If you think about if it has high frequency, then the wavelength should be shorter.

I: How about the energy and the wavelength?

M3: And then since umm. Frequency and wavelength are inversely proportional, that means energy and wavelength should be inversely proportional.

I: Do you know the equation that shows the relationship energy and wavelength?

M3: Oh. Here, I remembered just know [she wrote $E=h/\lambda$]

Student M3 used her mathematical model to recall the relationship between energy and frequency. To explain the frequency/wavelength relationship, on the other hand, she used information that she had memorized. After some thought, she could explain the relationship between frequency and wavelength. Finally, she used reasoning to find the relationship between energy and wavelength by using her knowledge of the energy/frequency and frequency/wavelength relationships, and she remembered the equation to support her response. However, she could not find or remember the equation that combined all three phenomena.

In the pre-questionnaire, the concept of the quantization of energy was described by Student M3 as “*Energy in chunks, so electron jump from different energy levels meaning they cannot have parts of that quanta.*” Although she said “energy in chunks,” she did not elaborate on the kind of energy she was referring to in either her written or verbal answers. Transcribed below are excerpts about energy quantization from the pre-interview with Student M3.

M3: I remember teacher once said that quantum means like things are coming chunks. So, when I think of quantization in energy, it just tells me what we learned the spectrum like you cannot... you have to go from here to here [she showed her drawing of energy levels, reproduced in Figure 5.3.4a] you cannot go in between or anything. It is like a package. You cannot break it down into smaller things. So, I think quantization of energy is like when electron go from shell to shell, they cannot be found between those, but they have to be found right there.

This verbal explanation illustrates that Student M3 had learned what quanta and quantization mean, and especially what they mean in the context of energy levels. However, the terminology she used to describe the quantization of energy was not completely scientifically correct. For example, instead of “energy levels,” she used the term “shell” in explaining electron transitions. After she engaged with a computer-based simulation about energy levels, Student M3 produced an energy level diagram (see Figure 5.3.4b) that was based on her observations. In her new energy levels model, she indicated that electrons transition after becoming excited, and she showed that electrons do not always jump down to ground state—in contrast to what she believed before the model-based instruction. In an inter-lesson assessment, we specifically asked students to describe energy states in an atom; Student M3’s response was “*→Energy states are unique to each element →Electrons only transition between states when enough energy*

is available. →Electron possess potential energy that is inversely proportional to distance.” From her answer, it is obvious that she changed her choice of words from scientifically incorrect to correct terminology. She used terms such as “transition,” “energy states,” and “electron potential energy,” which she did not utilize initially.

5.3.3 Lesson 3: Atomic Line Spectra and Energy Levels

Student M3’s model of atomic spectra prior to the model-based inquiry was in the hybrid model category. She knew that the dark lines in the sun’s spectrum occur because of quantized energy levels and the consequent absorption of photons.

M3: Only specific... So, I think because quantization of energy how like specific bars that were like... it would absorb or emit energy. And then since energy is inversely proportional to wavelength that means it goes to same wavelength since this is the constant. So, wavelength there is only at specific ones that will hit the bar and then only at those points it will ... the energy will be absorbed and create a dark line.

I: So, that dark lines mean that atom is absorbing or emitting energy?

M3: Absorbing energy.

Although Student M3’s reasoning was correct, her use of terminology showed some deficiencies. She used some ambiguous terms such as “specific bars,” “those points,” etc. In response to the question concerning the quantization of a hydrogen atom, she drew an absorption spectrum (see Figure 5.3.5).

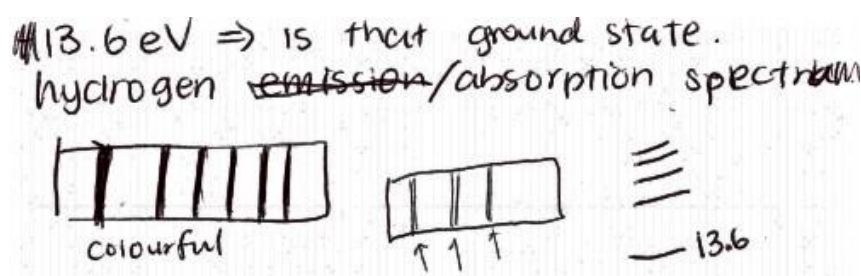


Figure 5.3.5: Student M3's initial model of an absorption spectrum

Her model shows equally spaced dark lines located on what she called a “colorful” base. When asked to explain her model, she said,

M3: Yeah, in chemistry they showed us like a picture of... this is like the color would be like color rainbow... kind of blended together at the background. And then there would be black lines. And then by looking at the location of the black lines you can know which element it is. And then for hydrogen, the black lines are... I think the other places electrons absorb energy to go to higher state. Because the photons, they do not exist in the black line. I think the electron absorb that energy.

I: So, are those lines the same for every element? Atom? or...

M3: No, I think they are different. So, that's how you can identify which element it is.

In this study, most students referred to their high school or college chemistry courses or to teachers when they explained their existing models. Student M3 was one of the students who used her chemistry background to explain atomic structure, energy levels, and atomic spectra. When she described spectra, she said that her teacher had shown a picture of rainbow colors blended together. Since she constructed her model based on a picture, she probably did not learn how those blended colors occur.

After completing the model-based inquiry activities, Student M3 started using more scientifically appropriate terminology when explaining her ideas about the absorption and emission process. In response to a question about the absorption and emission process, she answered, *“A photon (packet of energy) collides with atom exciting its electron to a higher level as it absorbs the photon. The electron emits a photon after some time (this cannot happen in ground state) and goes to a lower energy level. Not necessarily ground state, but eventually ground state.”* Student M3 used fewer ambiguous words, such as *“thing”*, *“it”* etc., and instead started using terms like photon, electron, higher level, lower level, and so on. Although she altered her model about

excited electrons going back to ground state, she still believed that the electrons eventually do go back to ground state. However, her answer to the next question indicated an inconsistency in her model concerning the electrons' final destination (see Figure 5.3.6).

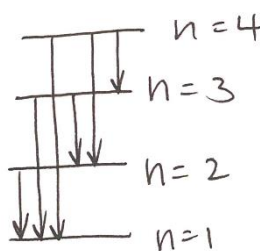


Figure 5.3.6: Student M3's model of electron transitions

Figure 5.3.6 shows that Student M3 had a target level electron transition model, which properly indicates the number of possible transitions between four energy levels as well as all possible jumps. Unlike her belief that electrons eventually go back to ground state, her model of electron transitions shows inter-state jumps as well.

Student M3's models of atomic spectra were also revised after she completed the model-based inquiry activities (see Figure 5.3.7).

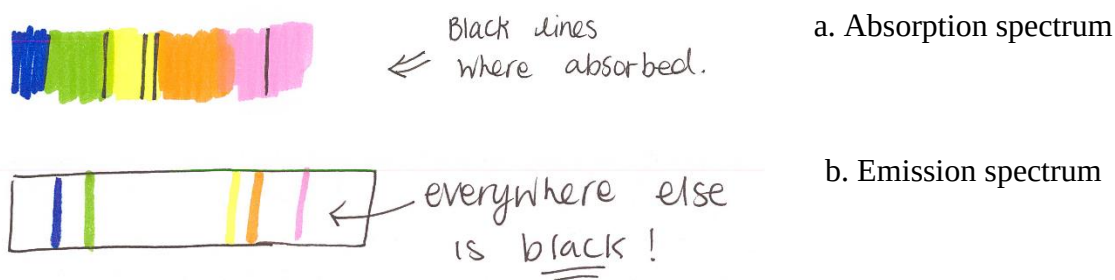


Figure 5.3.7: Student M3's depictions of atomic spectra

Student M3 drew absorption and emission spectra in which the absorbed and emitted wavelengths were not equally spaced, and instead of saying blended or rainbow

colors, she depicted the color sequence in a more accurate order. In the post-questionnaire, it was still challenging for Student M3 to match spectral lines with an energy level diagram. She picked two different energy level diagrams, which could correspond to six spectral lines on a spectrum (see Figure 5.3.8).

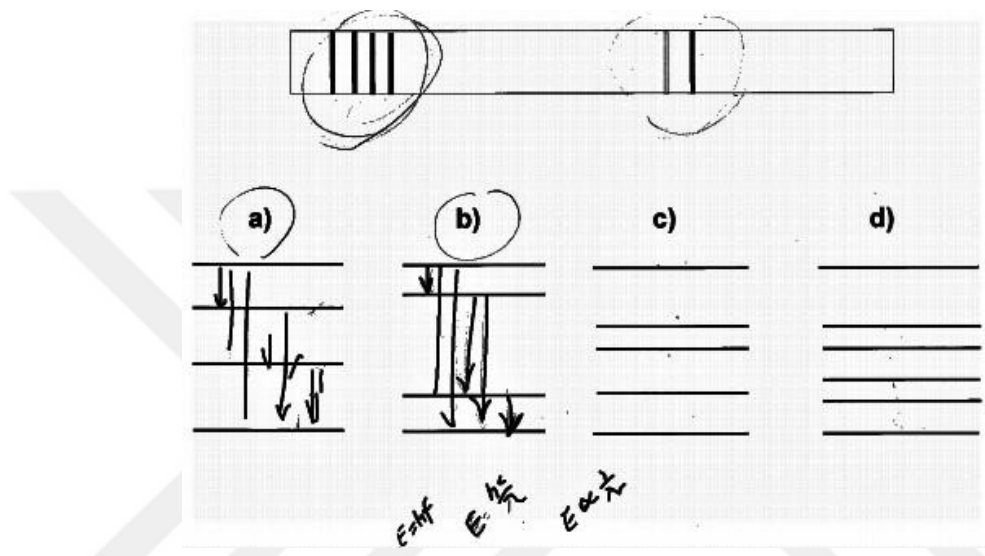


Figure 5.3.8: Student M3's answer about matching spectral lines and electron transitions

Although Student M3 correctly eliminated the options that have more than four energy levels and provided accurate reasoning about the number of possible transitions, she initially could not correlate the positions of spectral lines with the distances between energy levels. Her answer during the think-alone process was *a*. The transcription below presents how she evaluated, revised, and then refined her model during the think-aloud process.

I: Why did you chose a? Did you think that corresponds to these spectral lines?

M3: Umm... I chose a because like the distance between each like ... like around the same. So that would give you from here to here, here to here and here to here [she showed the jumps from 1 to 2, 2 to 3, and 3 to 4 in a]. If you like... lines over here. And gaps that would be greater would probably give you lines over here. But then I through

this question I did not really know I was doing. So, I am not sure.

I: How did you find these lines on the energy level diagram? What was your logic?

M3: Umm... I just looked at the distance of the lines which I am not sure...

I: What do each lines correspond?

M3: That's corresponding to the frequency of the photons that are emitted. And then which is related by this equation [she wrote $E = hf$]. So, or wavelength [she wrote $E = \frac{hc}{\lambda}$]. Yeah, with the

wavelength.

I: Those are emission or absorption lines?

M3: Emission lines. Yeah. So, it would be emitting at these wavelengths based on the energy difference between each level.

I: Why did not you pick those [other options]?

M3: Umm... I think I did not pick these two because there are 6 emission lines and then for these two there is different ways of transitioning between the...line emitting energy between the different levels, but then for these like there is more than 6. But then I guess like I guess these can be possible too.

I: Why?

M3: Because does not... I feel like I remember when I did one of the simulations they like emitted wavelength beyond the visible spectrum.

I: But we are just caring about these ones [by showing six spectral lines].

M3: Okay then I would just look at a) and b), because there are 6 emissions... different emissions over here, and then if you have four lines then you have 6 different possibilities.

I: Do these lines show that electron emits photon like this [transitioning from a lower level to a higher level]?

M3: Oh no, that's absorption. So, from... this would be like emitting [she drew arrows from the higher energy levels to the lower energy levels]. Umm I think there are only 5. No there is 6. Yeah [she drew the arrows for answer b too] actually may be it is b.

I: Why?

M3: Because energy and the wavelength is indirectly proportional, right? So than over here there is two, two of these energy emissions they are smaller compare to the rest of the four. And these four are around the same... the same like they are around the same looking at the graph. So, these four probably corresponding to these. And then these two are probably corresponding to this which has greater wavelength than this one. So, I changed my answer to b.

When Student M3 started thinking out loud, she stated that she was not sure about her initial response. When I asked her about her logic in choosing answer *a*, she said that she looked at the distances between the lines; however, she added that she was not sure—an indication of her dissatisfaction with her choice. When I asked her the reason that she had not chosen any of the other options, she explained that the last two energy level diagrams had more than six potential transitions and she referred to the simulation from the model-based inquiry. Later, in the think-aloud process, Student M3 started thinking about choice *b*, too, and she drew electron transition lines for *b*. Then, after recognizing that the lengths of the lines were different for each transition, she changed her answer from *a* to *b*.

5.3.4 Lesson 4: Bohr's Model of the Hydrogen Atom

Student M3's initial atomic model reflected a combination of Bohr's theory of the atom and a valence shell model. Although she did not specifically talk about the Bohr model in any of her verbal explanations, her hydrogen atom representation indicated that she was using a Bohr model. After she completed the model-based activities, in response to a question about the reasoning that Bohr used to explain what keeps electrons from striking the nucleus, she said, "*Angular momentum is conserved so orbits in lower states are stable. Energy levels are quantized so not all radius is possible.*". When I asked about spectral series, M3 illustrated very little understanding:

M3: Okay, I am sorry I have no idea what Lyman series are.

I: You have not heard it before?

M3: No, never hear of that. The only one that I have heard of is the last one [Pauli Exclusion Principle]. But then I did not find any description that actually fits what I was thinking.

I: Paschen series?

M3: Umm... No. I feel like I've heard it before. So, I put it like here

[describing the emission lines of a hydrogen atom as an electron goes from $n \geq 2$ to $n = 1$]

Initially, none of the students were familiar with spectral line series. Student M3 stated that she had not heard of the Lyman series prior to the pre-questionnaire. Even though she said she might have heard of the Paschen series, her answer showed that she did not know anything about that series either. After she completed the model-based activities, she was able to talk about the Lyman, Balmer, and Paschen series.

M3: The energy level of which they start at

- Lyman $n=1$ to $n=x$
- Balmer $n=2$ to $n=x$
- Paschen $n=3$ to $n=x$

Although Student M3 wrote down the starting level for transitions in each series, she indicated during the think-aloud process of the post-questionnaire that she did not understand what these series were.

M3: I really never really understood the series, but I just remember something about like Lyman is the one that starts from at 1. And the Balmer is the one starts 2, and the Paschen is 3.

I: Starts in what?

M3: Like the energy level. Like Lyman starts at $n=1$.

I: Starts? Okay, Lyman starts $n=1$ and do what?

M3: So, $n=1$ to n equals to some number and then...

I: What are you describing? You can do lots of things ... starting from $n=1$ to go higher energy levels? But what do you want to do? What Lyman series is really defining or describing?

M3: I don't know I feel like we've never like talked about that.

I: Never?

M3: Like I remember seeing the equations. But then I don't really remember actually understanding what they actually represent or meant

I: Really? We have talked about it couple times.

M3: I don't think. Yeah maybe I just did not really understand it.

One of the model-based learning modules covered all the spectral series as part of the Bohr atom lesson. However, there was no particular model-based activity for these concepts. The reason for the inefficiency of this part of the lesson might have been the brevity in talking about the concepts and the lack of an activity. The nature of the topic brings some limitations in designing a good model that would help students to understand the spectral series.

During the lessons, students derived Bohr's radius for a n^{th} energy level by using Coulombs law, centripetal force, and angular momentum (which was one of Bohr's assumptions). The derivation helped students to see how Bohr's assumptions consisted of mixed ideas from classical mechanics and quantum mechanics. This activity also helped them to answer the question in the post-questionnaire about defining Bohr's assumptions as classical and/or quantum physics. Student M3's response to this was "1. *Angular momentum is conserved* → *Classical physics in an orbit* 2. *Angular momentum is an integer multiple $\frac{nh}{2\pi}$* → *Mixture* → *Integer part based on quantum* 3. *electron orbits nucleus* → *Classical, planet model.*" Student M3 stated three postulates out of four. She correctly identified the second and the third postulates as a mixture and an expression classical mechanics, respectively. Her first assumption, on the other hand, was not completely correct. She stated that angular momentum is conserved instead of saying that the total energy remains constant despite acceleration around the nucleus. She also said that this postulate was inspired by classical mechanics, which is incorrect.

To see if the students could make connections between energy levels, radii, and electron energy, students drew graphs in an inter-lesson assignment relating orbit radius to energy level as well as orbit radius to electron energy. Figure 5.3.9 presents Student

M3's graphical depictions of electron energy against energy level (top) and energy level against Bohr radius (bottom).

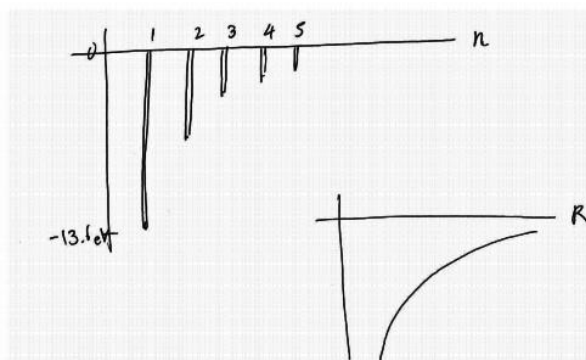


Figure 5.3.9: Student M3's graphs showing electron energy against energy levels and energy levels against Bohr radius

Student M3 drew a histogram graph to represent the energy of electrons at particular energy levels. Her graph indicated how she conceptualized quantized energy levels. Based on the histogram, she drew a second plot, which gives a scientifically accurate representation. Taking into account that these students did not practice plotting graphs based on their derivations, Student M3 showed quite successful performance in transferring her mathematical model into a graphical model.

5.3.5 Lesson 5: Wave Mechanics and the Hydrogen Atom (Quantum Mechanical Hydrogen Atom)

In the pre-questionnaire, Student M3 showed very limited knowledge about the quantum mechanical view of an atom. Her initial atomic model was a discrete entity (particle) model. Although she did not demonstrate any quantum views in any of her atom representations, she said, “*Electrons can behave like waves when not observed,*” in response to a question that asked for a description of an electron. Her detailed explanation during the think-aloud process was “*I wrote down because I was thinking*

about the double-slit experiment and the wave-particle duality. So, electron can behave like waves when they are not observed." Unlike M3's electron representations in her hydrogen atom and multi-electron atom depictions, she mentioned wave-particle duality and referred to the double-slit experiment. Transcribed below are interview segments representing Student M3's initial ideas about the uncertainty principle, Schrödinger's equation, wave function, and probability density.

M3: I don't know about wave function, but I have read somewhere that is the sum of all the possibilities... all the possibilities of each possible state. So, like for example you take the cat then it is like 0.5 times it is alive plus 0.5 times it is dead. I think that is the wave function is talking about.

I: Is it like the possibility of cat's dead or being alive?

M3: Yeah, it is the possibility of what you are going to find when you try to measure it.

I: What is the probability density then?

M3: Oh, sorry yeah the probability of where you are going to end up with that particular state. So, like there 50% you are going to find cat is dead and then there 50% you are going to find the cat is alive.

I: What is it? I am just confused about if it is wave function or probability density?

M3: Oh no, no. I only wrote about wave function, I did not write about probability density. I was talking about because I think the wave function describes... like all the probabilities added up.

I: Can you explain a little bit about probability density? Do you know what it is?

M3: I don't... I've never seen that term before.

I: And Schrodinger model?

M3: Umm...I only know the Schrodinger experiment for the cat.

I: What is that relationship between Schrodinger's cat and electrons or atom or anything in quantum mechanics? Why Schrodinger did bring up that thought experiment?

M3: I think he wants to show what is the difference between like when you observing something vs. when you are not. And then how the things like in the quantum world... a lot of things are happening at the same time. If you do not observe it, they are just kind of everywhere. So, for Schrodinger's cat, if you don't open the box than at the same time it is alive and it is dead, but once you open the box, you are forcing it to choose an option between being alive or being dead. And I think this relates back to double-slit experiment with the electrons. So, when you are not observing it, it will just

have interfering something. There is going to be a wave pattern on the wall. Even though you know you are just one electron, it should just go through one door. So, when you [are] looking at it, it does go through one door, but then when you don't look at it does not... it just acts as wave. So then, that's like it is going... it is like all possible states. But then when you do look at it you are forcing it to choose one of the doors. So, it has to choose one of the doors to go through. I think that's how they relate to each other. So, it is like... I don't know if that is true at all but since we said that we don't know the exact location of the electron, we can only know the probability of where it could be... it most likely [could be] found. I think when we [are] measuring it, we [are] forcing it to choose one of the locations to be in. And then that is ... and then one of the highest probability would be like the most likely place to find it.

Student M3 indicated that she had not heard the term probability density prior to the study. She explained wave function by referring to Schrödinger's thought experiment. Her knowledge was based on a piece of information that she had read somewhere. Her initial model of wave function showed that she might have confused wave function with the superposition principle when she said that it is the "*sum of all possibilities*" of finding an electron. She also frequently used the concept of possible states, most probably referring to quantum states, but without giving any further detail or description.

Schrödinger's equation and its assertion were unknown by almost all the students in this study. Student M3 showed a good understanding of the double slit experiment and what Schrödinger's cat thought experiment explains. When I asked her about Schrödinger's equation during the think-aloud process of the pre-questionnaire, she only talked about the thought experiment.

During the model-based activities, students engaged with physical models and visual representations to learn four quantum numbers. Figure 5.3.10 presents Student

M3's work, which shows orbitals and her calculations of the number of electrons in each level and sublevel.

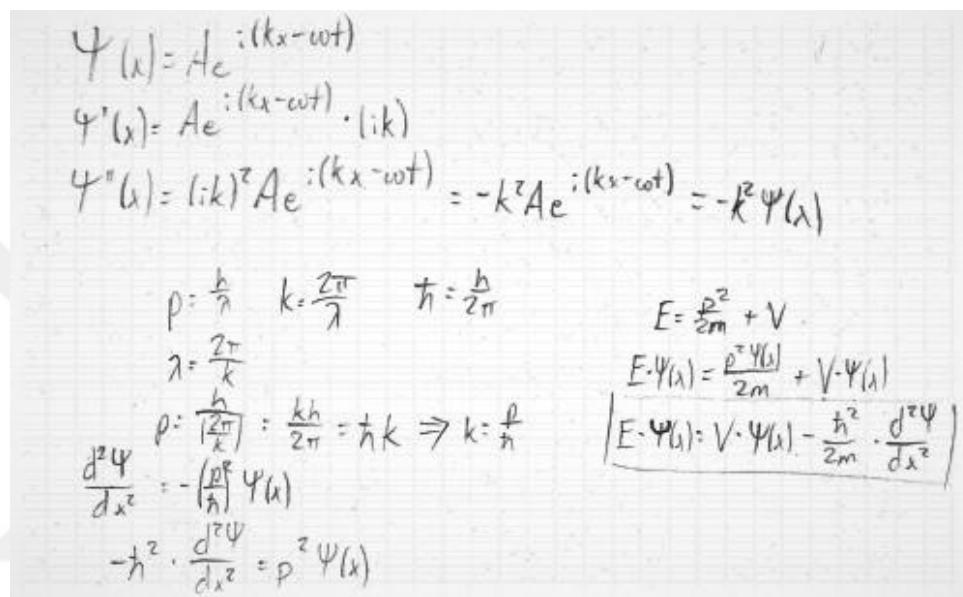
The 4 th energy level has 4 sublevels called:	- 4f, has 7 orbitals called 4f and can have 14 e ⁻ - 4d, 5 orbitals, 10e ⁻ - 4p, 3 orbitals, 6e ⁻ - 4s, 1 orbital, 2e ⁻
The 3 rd energy level has 3 sublevels called:	- 3d, 5 orbitals, 10e ⁻ - 3p, 3 orbitals, 6e ⁻ - 3s, 1 orbital, 2e ⁻
The 2 nd energy level has 2 sublevels called:	- 2p, 3 orbitals, 6e ⁻ - 2s, 1 orbital, 2e ⁻
The 1 st energy level has 1 sublevel called:	- 1s 1 orbital, 2e ⁻

Figure 5.3.10: Student M3's quantum numbers calculation table

Student M3 demonstrated a sufficient understanding of quantum numbers, including subshell names, the number of orbitals, and the total number of electrons in each energy level.

During the model-based inquiry, Student M3 made observations using the de Broglie and Schrödinger models. Her explanation of de Broglie's model was *"Most light passes by with no effect. Only some photons are absorbed when they are the potential electron locations move to a higher energy level. When the electron moves down, a photon is emitted."* Her explanation of Schrödinger's model was *"When certain photons are absorbed, the shape that demonstrates the potential locations of the electrons changes. It returns to its original shape and emits a photon."* Student M3's observational notes show that she understood both of the models and their assertions. She explained very well, for both models, how an orbital takes a different shape during the absorption and emission of (a) photon(s).

In another model-based inquiry activity, students performed a simple derivation of Schrödinger's equation by using basic knowledge of such phenomena as non-relativistic kinetic energy, de Broglie's wave equation, and wave function. Figure 5.3.11 shows Student M3's mathematical model for Schrödinger's equation in one dimension.



$$\begin{aligned}\Psi(x) &= Ae^{i(kx - \omega t)} \\ \Psi'(x) &= Ae^{i(kx - \omega t)} \cdot (ik) \\ \Psi''(x) &= (ik)^2 Ae^{i(kx - \omega t)} = -k^2 Ae^{i(kx - \omega t)} = -k^2 \Psi(x)\end{aligned}$$

$$p = \frac{h}{\lambda} \quad k = \frac{2\pi}{\lambda} \quad \hbar = \frac{h}{2\pi}$$

$$\lambda = \frac{2\pi}{k}$$

$$p = \frac{h}{\frac{2\pi}{k}} = \frac{kh}{2\pi} = \hbar k \Rightarrow k = \frac{p}{\hbar}$$

$$\frac{d^2\Psi}{dx^2} = -\left(\frac{p^2}{\hbar^2}\right) \Psi(x)$$

$$-\hbar^2 \cdot \frac{d^2\Psi}{dx^2} = p^2 \Psi(x)$$

$$E = \frac{p^2}{2m} + V$$

$$E \cdot \Psi(x) = \frac{p^2 \Psi(x)}{2m} + V \cdot \Psi(x)$$

$$\boxed{E \cdot \Psi(x) = V \cdot \Psi(x) - \frac{\hbar^2}{2m} \cdot \frac{d^2\Psi}{dx^2}}$$

Figure 5.3.11: Student M3's derivation of Schrödinger's equation

After deriving Schrödinger's equation, Student M3 was again asked to describe Schrödinger's equation and wave function. Her responses were respectively, the "Probability of all possible quantum states a particle could have?" and the "Sum of probability of a possible quantum states a particle could have?" The question marks at the end of the statements probably indicate her uncertainty about her answers. She gave almost the same definition for both Schrödinger's equation and wave function. However, in the post questionnaire she was able to give some definition to probability density and wave function concepts.

M3: We know that uncertainty principle states that the more you know the position the less you know about momentum and vice versa. And

then at a macroscopic state, the uncertainty principle does not really apply. Because we know the position and the momentum at the same time for macroscopic objects

I: What is quantum mechanics?

M3: That is physics describes the world at the microscopic view.

I: What do you know about Schrödinger equation, wave function and probability density?

M3: They describe the probability of where you can find out an electron. They describe the probability of where the electron could be located.

I: Schrödinger equation, wave function or probability density? Which one are you talking about?

M3: Probability density?

I: What is the probability density again?

M3: So, it just tells you how probable it is to find an electron at certain location.

I: How about wave function?

M3: Does not the wave function also describe that like the possibility of something in each state? No? And then for Schrödinger I know that we derived it, but I was not really sure what it was talking about.

Student M3 gave a complete and appropriate definition of the Heisenberg uncertainty principle. However, her statement about the Heisenberg uncertainty principle and macroscopic objects illustrated that she was still under the influence of a deterministic perspective. M3's verbal explanation of probability density also indicated some incomplete or incoherent understanding. In her first definition, she said, "*the probability of where the electron could be located.*" When I asked her to explain it a second time, she said, "*how probably it is to find an electron at certain location.*" In her second statement, she refined her explanation and mentioned finding an electron in a certain location. In the post-questionnaire, she also indicated that she did not have a sufficient understanding of quantum numbers, Schrödinger's equation, and wave function.

5.3.6 Lesson 6: Multi-Electron Atom

Electron configuration and orbital notation are good indicators of a student's understanding of the quantum-mechanical atom model. Figure 5.3.12 presents Student M3's models of electron arrangement and orbital notation in the pre- and post-questionnaires and in an inter-lesson assessment.

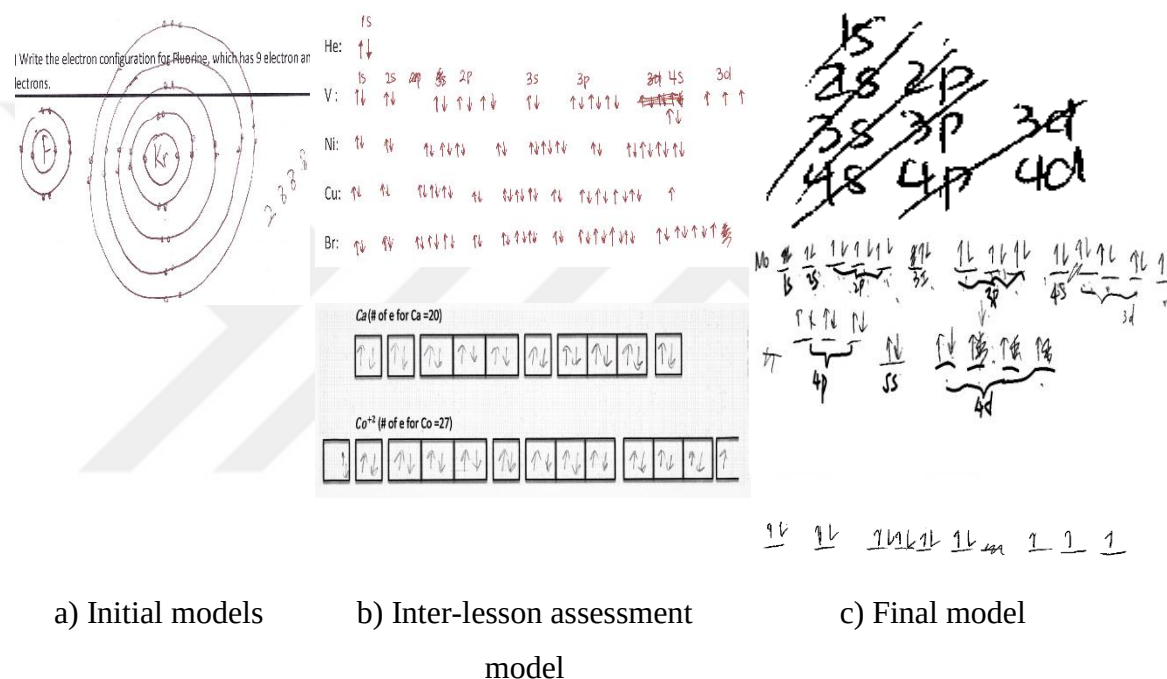


Figure 5.3.12: The evolution in student M3's electron configuration and orbital notation models

Student M3 drew her models of fluorine and krypton atoms as an answer to the question about electron configuration in the pre-questionnaire.

M3: I think like how many electrons goes into each shell. Like that?
 Or...we saw chemistry where you just drew fluorine and then there is two electrons in the first shell. And then was not it 8 or was it 4?
 [She drew her Fluorine atom with electrons on it] And the krypton, I don't know what the... it is not K. So, I assume it that [She wrote Kr for krypton and drew her Kr atom with electrons on it.] I am not sure if it goes beyond 8 anymore. It is 33, no 26 [She counted the number of electrons she drew around the Kr.]

I: Why you think these electrons are paired up but those are like three

electrons? Why did you draw two electrons here together and here three electrons together?

M3: For ...if you just ignore the outer ring like the inside part, I am just trying what I remember from the chemistry junior year. Then I remember that's how we drew in junior year. And then, for the last shell, because I think it goes from like 2 electrons and then 8 [electrons], and then 8, and then I am guessing that it is 8 [electrons], but I feel like I remember that after that it changes to bigger number. So, that's why after filling in the 8 [electrons] I did not move on the next shell I just kept going with the remain number of electron that I have left.

I: Okay. Again my question, let's ignore the outer shell but why two electrons are paired up for inner shells?

M3: Hmm [She stopped to think.]

I: Why not here [pointing at the electrons on the innermost level]? Why two electrons do stay away from each other here, but here they are paired up?

M3: For this one, it makes sense that they are farthest from each other because they have the same charge, so they are going to repel.

I: So, how do they stay together here then?

M3: I think it is just the way of representing it, because technically that is not going to be exactly where we are going to find it in anyways. So, I think this might be just the way they are like to be represented in chemistry... rather than exactly just representing the exact location, because that is you cannot find that anyways.

I: Do you know anything about orbital notation?

M3: [She shook her head meaning no.]

Her verbal explanation indicated that Student M3 did not know the correct scientific representation for electron configurations. In accordance with her models of hydrogen and a multi-electron atom, she drew valence-shells with Lewis dot representation. She located the electrons on circular orbitals around the nucleus in the configuration 2-8-8-8-10. Except for the last and first shells she paired up all the electrons, with two on each side of the nucleus (top, bottom, left, and right). Her reasoning for this model was that electron pairs repel each other because of the opposite electrical charge. When I asked her about the last shell, M3 said that the electrons were not in exact locations.

After going through the model-based inquiry activities, there was a remarkable change in Student M3's model of electron configuration. Her models in an inter-lesson assessment and the post-questionnaire were close to the target model.

M3: Well, this is very messy. Okay. Yeah so, that's 1s 2s 2p 3s 3p 4s 3d 4p 5s 4d

I: How many electrons?

M3: Oh. I think I might have lost one somewhere. Wait so, is it 42? 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, ... So, actually ...there, I think that works. I am just missing one over here. So it has 1, 2, 3, 4, 5, 6.

I: When I ask you to draw orbital notation...

M3: Oh sorry. I did not I did not see the part [she showed her orbital representation]. Hmm... Orbital notation.... I don't remember how to do that.

I: What did you draw here [indicating her orbital notation representation]? Is this electron configuration or orbital notation?

M3: Is not this thing electron configuration [showing her electron configuration representation]?

In both the inter-lesson assessment and the post-questionnaire, Student M3 demonstrated an understanding of principle and orbital quantum numbers. Although she ordered the shells and orbitals based on the number of electrons that each orbital can hold, she did not include these numbers in her representation. Moreover, Student M3 successfully applied the Aufbau and Pauli principles as well as Hund's rule in her models of electron arrangement and orbital notation. However, in the inter-lesson assessment, she used orbital notation instead of showing electron configuration. In the post-questionnaire, she also used both types of notation in the electron arrangement question. Her first response to the orbital notation question was that she did not remember how to do orbital notation. After a short time of confusion about electron arrangement and orbital notation, she was able to tell which one was which.

In another activity, I asked the students to draw a fluorine atom based on their understanding of electron arrangement. Figure 5.3.13 presents Student M3's drawing of 1s, 2s and 2p orbitals.

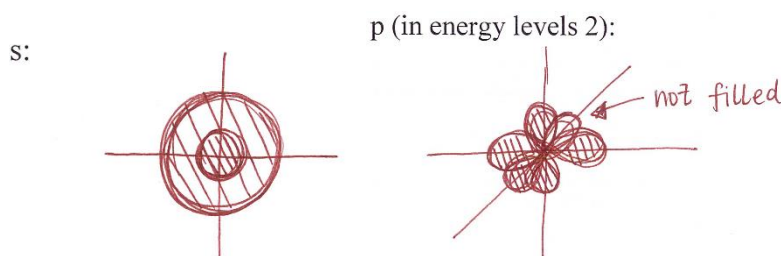


Figure 5.3.13: Student M3's fluorine atom model

In her drawing of orbitals, Student M3 colored the inside of the orbitals evenly. This means that although she was showing the probable places that electrons could be found, she did not consider probability density. For the p-orbitals, she indicated that one side of a p_z -orbital is not filled. Although Student M3 did not mention probability density in any of her atom models, she showed it for an s orbital when I specifically asked about it in another question (see Figure 5.3.14).

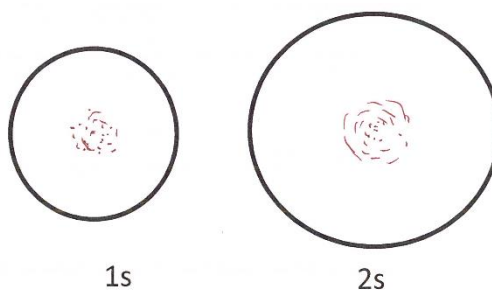


Figure 5.3.14: Student M3's probability density model

Probability density was a challenging concept for most students. The classical view concerning the electronic force between protons and electrons was strongly rooted in the students' conceptual understanding. Student M3 demonstrated a similar classical

view and said, “*I put them concentrated in the middle because closer to the nucleus means less energy required.*” Her reasoning showed similarities with her initial idea about electrons wanting to return to ground state after becoming excited by (a) photon(s) because it is the most stable energy level.

Although Student M3’s learning pathway followed a good progression, her final multi-electron atom model was exactly the same as her initial model of a multi-electron atom. Transcribed below are excerpts from the post-interview with student M3 about her multi-electron atom model.

M3: Umm... I drew it like the Bohr model. So, two electrons, and the 8 electrons and the two more.

I: Why did you draw a Bohr model?

M3: I did. I drew Bohr model?

I: Yeah, I mean why did you choose that model?

M3: That’s the model that I learned when I was young.

I: Okay.

M3: Easier to view even though that is not exactly where actually be.

I: So, where they are actually?

M3: We don’t know exactly where. We only know that there is somewhere in that orbit.

Since the Bohr model is commonly used by teachers and instructors for the purpose of simplification, students feel more confidence using this model even though they are aware that it does not represent a real atom and that electrons are not located in specific places.

5.4 Evaluation of Student M4’s Model

Student M4 was a physics freshman student during the spring of 2016. He took an AP chemistry course in high school and enrolled in PHYS1H and PHYS2H in college. He notified us that he had learned some atomic structure concepts as part of his AP chemistry course. He was one of the most motivated and actively involved students

in the study. Before he attended the model-based inquiry lessons, he presented a mixed (classic and quantum mechanics) model, which seemed to be very widespread among students. During the pre-interview, he used terminology such as orbit, orbital, shell, electron cloud, etc., but he was not sure about their proper usage. Student M4's early atom models are presented in Figure 5.4.1.

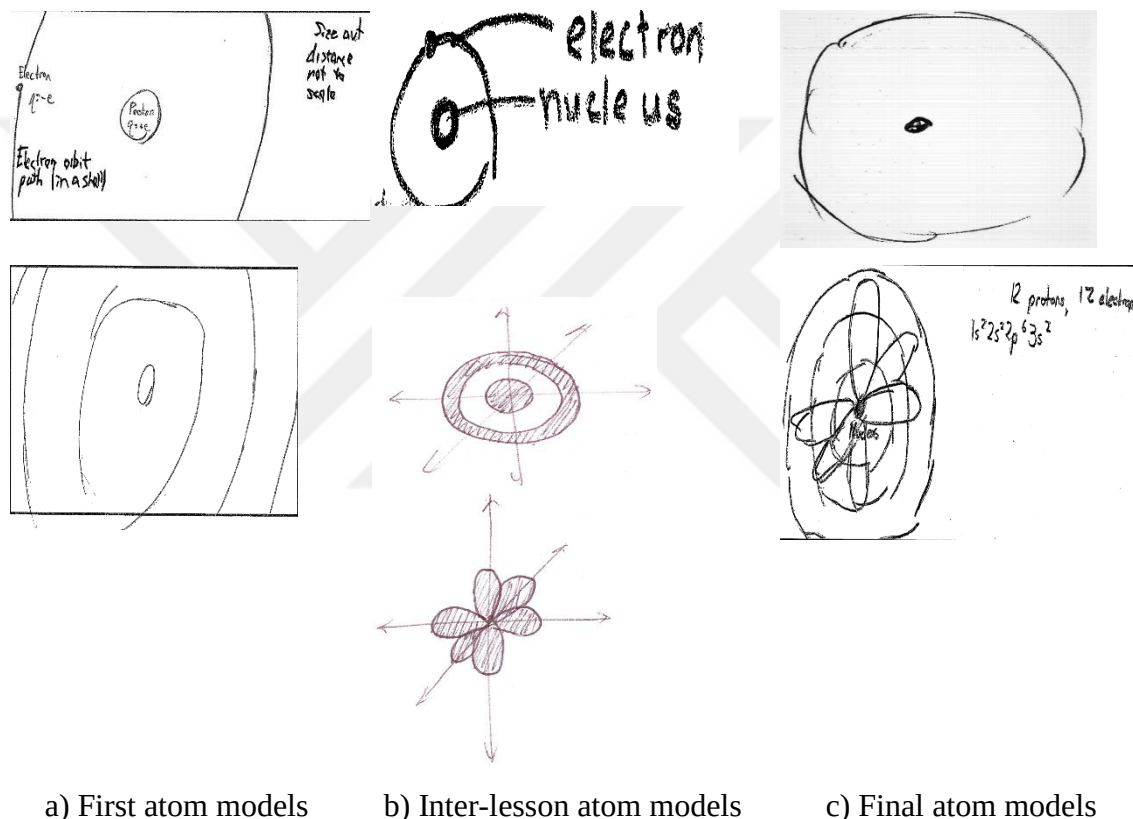


Figure 5.4.1: Student M4's atom models

Student M4's initial atom model was a hybrid model in which he combined the Bohr model and orbital concepts. For his hydrogen atom, he labeled the circular line around the nucleus as an “*electron orbit path (in shell)*.” This indicates that he was still using the Bohr model, orbits and shell for the circular paths even though he knew that electrons possessed specific amounts of energy. Bohr's discrete energy levels were shown in Student M4's multi-electron model (see Figure 5.4.1a, bottom), but he did not

draw them as complete circles. He had the conceptual understanding that electrons are moving on circular paths in different energy levels. He said, *“I guess the electrons would be at different energy levels. So there be ... maybe one orbital there and then the second one farther away.”* In his final models, he drew hydrogen and magnesium atoms using orbital representation. He did not illustrate probability density but also did not show electrons in specific locations.

5.4.1 Lesson 1: Early Atomic Models

In the first model-based inquiry activity, Student M4’s prediction about the Thomson atom model was *“if it goes through (1) ball can be broken down into smaller parts (2) something may block its path (3) it may go through smoothly.”* He stated the different possible situations that he might encounter. When he made observations, his notes indicated that he had another assumption in mind that he did not include in his predictions. He wrote, *“I tried poking through the center first b/c I thought that if anything is inside, the biggest possibility is center- but it went through. I found that there are 2 things blocking on opposite ends of the ball.”* Student M4’s presumption demonstrated his prior knowledge about the common model of the atom. However, he recognized that there was not an object at the center of the physical model. He only discovered two small objects inside the spherical foam.

As in his previous prediction, Student M4 had three predictions related to the electron beam cathode ray activity. His predictions were *“(i) if neutral, travels straight, (ii) if negatively charged, travels towards cathode, (iii) if positively charged, travels towards anode.”* Unlike the other students, Student M4 did not mention magnetization in his prediction. He assumed that the small balls could be neutral or negatively or

positively charged, presumably after seeing the positively and negatively charged plates. After completing his observations, he recorded that *“Balls stick to positive. Faster balls deflected first then stick to positive.”* None of the students except Student M4 commented about how the speed of the balls affected their deflection. When I asked about the relation of this activity to electron motion, he said, *“electrons will be attracted to anode and repelled from cathode. Their speed determines how much they are deflected/ how quickly they get attracted.”* Student M4 held to his idea that the speed of the electrons informs how much and how quickly they are attracted to the positively charged plate. In an inter-lesson assessment, he explained the reason for the glowing beam being repelled by the negatively charged plate, writing, *“The glowing beam was composed of negatively charged electrons. According to Coulomb’s law the electrons experienced a force away from the negative plate.”*

Student M4’s prediction for the Rutherford atom model was *“Go through smoothly if nothing inside. I expect something in center to block skewers.”* It showed similarities with his assumptions for the physical Thomson model. After making his observations on the physical Rutherford model, he said, *“Something inside, but location not constant. A lot of space inside.”* He also drew a model based on his observations (see Figure 5.4.2).

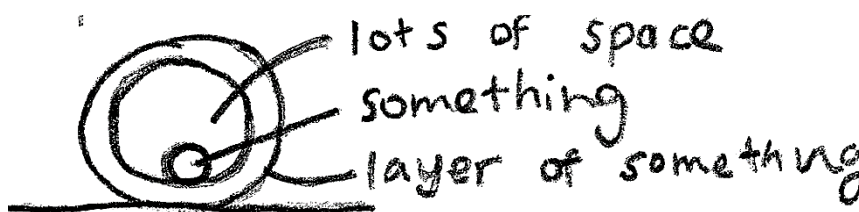


Figure 5.4.2: Student M4’s model of Rutherford’s atom

Student M4's drawing of the atom showed consistency with his observational notes. There is a big empty space and the nucleus rests at the bottom of the empty space.

Student M4's observational notes for the Rutherford atom scattering simulation were "1. *When he gets close, they deflect* → *They don't go through* [when the number of protons and the number of neutrons are both 20]. 2. *Deflection increases, alpha particles don't get as close* [when keeping the number of neutrons, the same but increasing the number of protons]. 3. *# of neutrons did not affect anything* [when keeping the number of protons, the same but increasing the number of neutrons]. 4. *Deflection increases, same as # 2* [when the numbers of protons and neutrons are both increased]. 5. *Energy low* → *gets deflected before getting closer. High* → *gets deflected after getting closer.*" In an inter-lesson assessment, his answer concerning Rutherford's assertions about the atom and nucleus was: "Rutherford's experiment showed that the majority of the atom is empty space and that the most massive part, the nucleus, has a positive charge." In his response, Student M4 again mentioned the big empty space and the positively charged nucleus, which is also very massive. However, his prediction of the results of Rutherford's alpha scattering experiment if the Thomson atom model were correct indicated his lack of understanding about why alpha particles are scattered by gold foil atoms. He said, "*Almost all alpha particles should have been repelled back to the general direction of the source or stopped by the gold foil.*" Although he knew that the Thomson model did not include a massive nucleus in the center, he still thought that all alpha particles would be reflected or stopped by the gold foil atoms.

After the model-based inquiry activities, he started to consider the earlier atomic theories according to their pros and cons. *“Thomson's model successfully identified the existence of separate positive and negative portions of the atom but failed to properly describe them. Rutherford's model was a more accurate representation of the location of the negative electrons and positive nucleus but misrepresented electron motion.”* This statement from the first assignment shows that Student M4 was able to understand the consequential process in the development of atomic models, but was still confused about the location of electrons.

Finally, Student M4's reasoning about why the planetary model was not accepted was *“Electron attracted to proton as it around the proton, eventually getting closer and finally annihilating each other.”* His answer indicated that he understood that electrons would have a spiral motion around the nucleus and collapse into it when they got close enough. However, he did not explain why electrons would make a spiral motion around the nucleus or why they lose energy while in circular motion, even though he calculated electron speed and kinetic energy (see Figure 5.4.3).

$$\begin{aligned}\frac{kqQ}{r^2} &= \frac{mv^2}{r} \\ \sqrt{\frac{kq^2}{m}} &= v \\ v &= 1.6 \times 10^6 \text{ m/s} \\ KE &= \frac{1}{2} m_e v^2 \\ &= 1.15 \times 10^{-18} \text{ J}\end{aligned}$$

Figure 5.4.3: Student M4's mathematical representation of the planetary model

In his calculations, Student M4 used the electrical force between protons and electrons and centripetal force to find the electron's velocity. Then, he calculated the

electron's kinetic energy by using the electron's velocity and the non-relativistic kinetic energy formula.

5.4.1 Lesson 2: Energy Levels and Quantization

Student M4's concepts of energy levels and quantization prior to the study were incomplete. When he was talking about his response to a question about the quantization of energy, he showed some uncertainty in his reasoning.

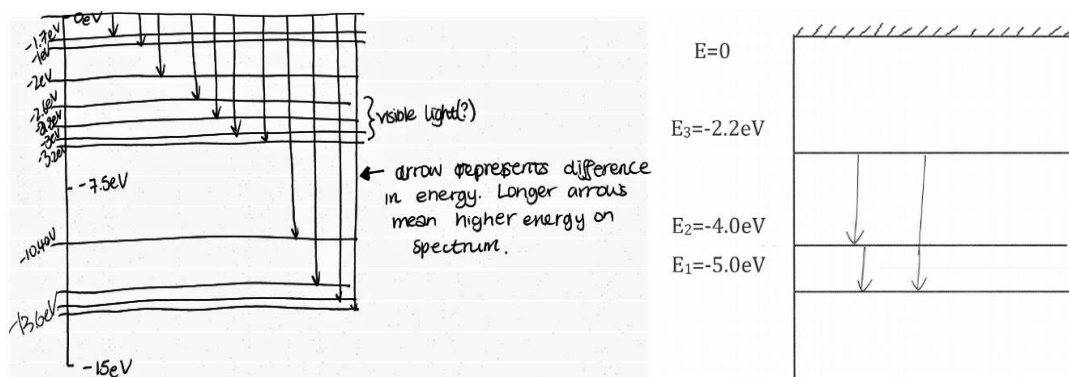
M4: It's hard to... it is sort of that energies given described by certain levels like... energy can only be at... I am not sure I can describe it properly.

I: Okay. When we asked how is energy quantized in a hydrogen atom, what did you say?

M4: So the electrons in hydrogen atom can only orbit at certain distances. That can only have the certain energies. So like one of the later questions is talking about energy states it can be at the lowest energy state or it can be at the higher one, but it can't be anywhere between these energy states.

While Student M4 could not properly explain the quantization of energy, his explanation was pretty accurate for quantization in a hydrogen atom. However, he indicated he had a discrete entity model in mind when he said, "*electrons in hydrogen atom can only orbit at certain distance.*"

Student M4 did not draw an energy level diagram when he answered the pre-questionnaire questions. His energy level models during the model-based inquiry and inter-lesson assessment are presented in Figure 5.4.4.



a) Energy levels model from a worksheet

b) Energy levels model from an
inter-lesson assessment

Figure 5.4.4: The evolution of student M4's energy levels model

After engaging with the computer-based simulation, Student M4 drew a diagram in which all the electrons jump down to lower energy levels (Figure 5.4.4a). He indicated the visible light interval and the corresponding energies. He represented electron transitions with arrows and explained this by saying, “*Arrow represents difference in energy. Larger arrows mean higher energy on spectrum.*” At the end of the model-based activities, he sketched another energy level diagram. This time, he showed electron transition from the second and third energy levels to the lower energy levels. Below, an excerpt from an interview with Student M4 is given as an example of his initial conceptual understanding of electron transitions and the relationship between frequency, energy, and wavelength.

I: What happen if an electron jumps down from one energy state to lower energy states?

M4: Umm... then the atom would release a photon of energy that's equal to difference between the high-energy states minus low energy state. So energy is conserved. And it just releases a photon.

I: What can you tell about the relationship between energy and wavelength? Or frequency?

M4: It's higher... higher frequency which is lower wavelength and higher energy. All are the same... roughly. An atom has higher energy

would have higher frequency in the lower wavelength or not atom photon.

I: Do you know it based on your memorization or do you have any equation to support that?

M4: There is an equation and I think it's something like wavelength times frequency....

I: Can you try to write here?

M4: Yes... umm... [He wrote $\lambda\nu = c$] that maybe or c is the speed of light?

I: Okay

M4: I don't remember specifically but I think it is roughly ...

I: How about the relation with energy?

M4: I don't think I have an equation for that. Not of top of my head.

Student M4's model of electron transitions from higher energy levels to lower energy levels is very close to the target model. He mentioned that an electron loses its energy when it jumps down to a lower energy level and since energy is conserved, this energy is converted to a photon.

In response to a question about the relationship between frequency, wavelength, and energy, Student M4 said that they are all the same and then added the term "roughly." This use of terminology confirmed that his initial model about the relationship between these three concepts was not complete, even though his verbal explanation seemed to be correct. When I asked the student to write an equation showing the relationship between frequency and wavelength, he could write the equation with just a little hesitation concerning the speed of light. For the relationship between energy and frequency or wavelength, he said he did not remember the equation.

After engaging with the model-based inquiry activities, Student M4 was able to calculate the wavelength of a photon released by an electron transitioning from level $n=3$ to $n=2$ by using the photon energy equation (see Figure 5.4.5).

Handwritten mathematical model of photon energy:

$$E_3 \text{ to } E_2: -2.2\text{eV} - 4\text{eV} = 1.8\text{eV difference}$$

$$E = \frac{hc}{\lambda} \quad \lambda = \frac{hc}{E} = \boxed{690\text{ nm}}$$

Figure 5.4.5: Student M4's mathematical model of photon energy

The type of energy that electrons gain or lose during their transition between levels is not an easy idea for students to conceptualize. Most students believed that electrons possess kinetic energy due to their motion, and that they lose or gain kinetic energy when they get closer to or farther from the nucleus. Student M4's response to a question asking whether there is a limit to the number of wavelengths emitted was "Yes. *An electron with sufficient kinetic energy will not be contained by attractive electric force with the proton. So, there is a maximum energy level.*" This explanation suggests that he believed that if an electron gained enough kinetic energy it could leave the atom (escape from the nucleus' electrostatic attraction). He did not invoke the potential energy of electrons at all.

5.4.3 Lesson 3: Atomic Line Spectra and Energy Levels

Student M4 exhibited a conceptual understanding of energy levels in terms of discrete entity and quantum-like models. Prior to the study, he indicated a good conceptual understanding about the absorption and emission of energy, but he did not know why electrons lose energy when they jump down energy levels.

I: Is it possible to jump from 4 to 2?

M4: I think so.

I: How do you think that electron jump down or jump up?

M4: If it would have go from 4 to 2, it just... I don't know. It loses the

energy. I am not specifically sure why, but ... yeah, I don't know the mechanism behind that completely.

Although Student M4's model of electron transitions during the emission process was correct, he showed deficiencies in accurately explaining the reason for energy being lost. Furthermore, his initial model indicated that absorption is not necessarily followed by emission.

(Q: In 1802 William Wollaston noted that the appearance of dark lines in the spectrum of sunlight. These lines are due to the presence of certain chemical elements in gases surrounding the sun. How did you explain why sharp dark lines appear only at specific wavelengths?)

M4: So that goes back to the energy states... Energy levels the electrons. Similar to how one electron drops down the energy levels releases a photon. The electron can also move up to a higher energy state by absorbing photon that has a specific energy. So, at a specific wavelength the photons of that specific energy and if there are specific elements surrounding the sun than photons would be absorbed by those elements and either not released again or scattered in a different direction. So it looks like there are lines in the spectra

Student M4 successfully explained the dark lines in the Sun's spectrum by explaining the absorption of energy by the elements surrounding the Sun. However, he stated that those elements might not release the absorbed energy or that they may scatter it in different directions.

(Q: How a comparison between the spectrum of sunlight dark lines with spectrum of light from Sodium lamp can identify that sodium is one of the elements in the sun's atmosphere.)

M4: The sodium lamp will... sodium lamp functions by the electrons in sodium atoms moving from higher energy levels to lower energy levels and releasing photons that are equal to the energy difference, like I said before. And so that those photons describe the... that describes the difference in energy states specifically for sodium. So, the energy of those photons will correspond to the wavelengths that are missing from the sun's spectrum. If sodium is in the atmosphere.

I: How do we identify sodium? How do you know it is not helium?

M4: If I recall correctly, sodium and helium would have different wavelengths. Different energies in the... different energy states. So,

the difference between these energy states would also be different. So, no two elements would have exactly the same emission spectrum.

In another question, Student M4's reasoning when comparing spectral lines in sunlight and light from a sodium lamp indicated that his model of atomic spectra was correct but not complete. When I asked him what the difference is between sodium and helium atoms, he doubtfully stated that these two elements have different spectra. At the end of the model-based learning module, Student M4 refined his model and confidently said, *"I mentioned that for all elements they have energy levels are different energies. So, the gap between them is different for all different elements. For example, hydrogen and neon would have different wavelengths of photons that they can absorb or emit."* With this explanation, he not only revised his model of the atomic spectra of different elements, he also supported his model with proper reasoning by saying that each element has different energy levels and therefore releases photons of different wavelengths.

Figure 5.4.6 presents Student M4's drawing of his model of absorption and emission spectra from an inter-lesson assessment.



Figure 5.4.6: Student M4's atomic spectra models

The color choices in both the absorption and emission spectra show his conceptual understanding of the wavelengths of each color and their order in the spectrum. However, his final model of the relationship between electron transitions and spectral lines was still incomplete.

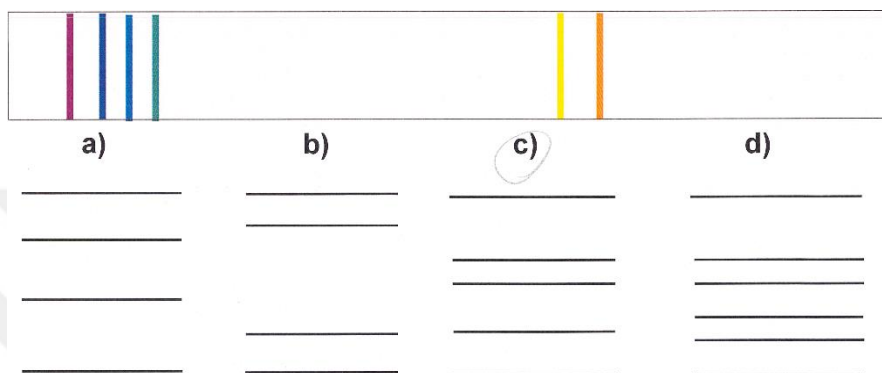


Figure 5.4.7: Student M4's final model of emission spectra & electron transitions

Student M4 chose a diagram that had more than four energy levels, which allows for more than six transitions. Although he correctly answered a question in the inter-lesson assessment that asked for the number of possible transitions among four energy levels, he could not transfer his model to answer this question. The transcription below is given to show Student M4's reasoning for choosing this option.

M4: I chose c, but I am not entirely certain.

I: Okay, what was your reasoning?

M4: The two ... basically two groups of wavelengths that can be absorbed which means that they are ... what you can tell is that all four of these for example are fairly low energy photons. And they all have a similar amount of energy which would mean that the gap in the energy level diagram would be somewhat smaller and there would be four gaps that are relatively similar size. And these two are relatively similar in size although one is larger than this one. But the gap is much larger because the energy of the photon is higher. I think c is the most reasonable at the time.

I: How many transitions do you think there are in the spectrum?

M4: In this one there are six. Here, probably more than six, but ... I don't know.

In this transcript, Student M4 displayed some incorrect knowledge in suggesting that the four short wavelengths that were close to each other were the low energy photons. Following his inaccurate model, he also thought that the distances between the four energy levels related to these wavelengths should be smaller. His second inaccurate idea was that there should be four levels corresponding to the four wavelengths. When he was forced to think how many possible transitions there were in the option that he chose, he realized that there should be more than six transitions, but he could not give a sufficient explanation for this.

5.4.4 Lesson 4: Bohr's Model of the Hydrogen Atom

Like most of the students, Student M4's initial sketches of atoms reflected many aspects of the Bohr model. While his hydrogen atom model had one circular electron orbit/path, his multi-electron atom model had multiple quantized circular orbits. Yet, Student M4's knowledge of Bohr's model was limited to just his atom representation. Student M4's pre-questionnaire responses and our discussion during the model-based inquiry activities revealed that he did not know about any of the spectral line series or Bohr's assumptions that led him to his atomic theory. After the model-based learning modules were completed, he still showed a lack of understanding, even though he was able to briefly explain what spectral line series are.

M4: So, in the equation for wave... I don't remember specifically what it is, but I think something like one over wavelength equals Rydberg's constant times one over ... something like that. And for the difference series... I think the Lyman series this first n would be 1 because it is from... it transitions from the first energy level and then the others will be 2 or 3 or 4 just depending on what transitions here.

I: Hmm hmm.

M4: And the different lengths are just based on the energy levels.

Student M4 tried to explain his understanding of spectral line series using their equation, but he was not able to remember all the components of the equation. He simply stated that the Lyman series starts at the first energy level and the others start at the second, third, and fourth levels.

During a model-based inquiry activity, he calculated the Bohr radius and electron speed for each quantized level (see Figure 5.4.8).

$$\frac{ke^2}{r} = mv^2$$

$$\frac{ke^2}{r_n} = \frac{m n^2 h^2}{(2\pi)^2 r_n^2 m^2}$$

$$\frac{ke^2 (2\pi)^2 m}{n^2 h^2} = \frac{1}{r_n}$$

$$\frac{1}{r_n} = \frac{ke^2 m (2\pi)^2}{n^2 h^2} = 1.178 \times 10^{-10} \frac{1}{n^2}$$

$$r_1 = 5.3 \times 10^{-11} \text{ m}$$

$$r_2 = 1.92 \times 10^{-10} \text{ m} \quad 2.12 \times 10^{-10} \text{ m}$$

$$r_3 = 4.31 \times 10^{-10} \text{ m} \quad 4.77 \times 10^{-10} \text{ m}$$

$$r_4 = 7.66 \times 10^{-10} \text{ m} \quad 8.49 \times 10^{-10} \text{ m}$$

$$v_1 = 2.19 \times 10^6 \text{ m/s}$$

$$v_2 = 1.09 \times 10^6 \text{ m/s}$$

$$v_3 = 7.28 \times 10^5 \text{ m/s}$$

$$v_4 = 5.46 \times 10^5 \text{ m/s}$$

$$L_n = r_n m v_n = n h / 2\pi$$

$$v_n = \frac{n h}{2\pi r_n m}$$

$$\frac{h}{2\pi m} = 1.16 \times 10^{-4}$$

$$v_n = \frac{h}{2\pi m} \left(\frac{n}{r_n} \right)$$

Figure 5.4.8: Student M4's mathematical model for Bohr radius and electron speed

Based on his calculations and energy levels diagram of a hydrogen atom, Student M4 was asked to decipher the relationship between electron potential energy and radius, thinking in terms of Bohr's theory. He demonstrated a sound understanding of the relationship by saying, "Potential energy decreases as radius increases. When radius approaches to infinity, potential energy becomes 0." With this statement and his

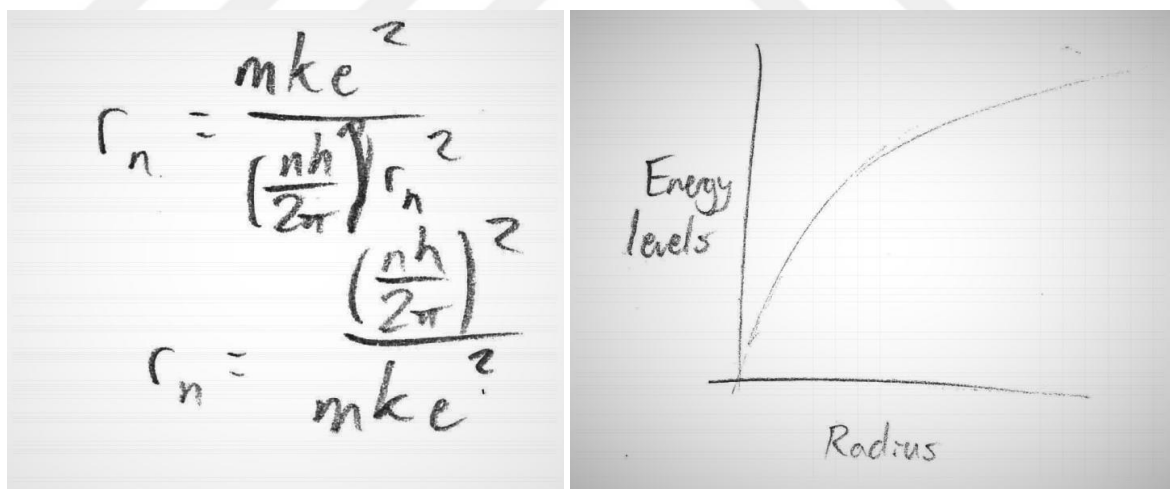
response to another question (see Figure 5.4.9), Student M4 was able to connect electron potential energy to electronic attraction force.

$$F_1 > F_2 > F_3 > F_4 \dots > F_\infty$$

As $n \rightarrow \infty$, Force becomes weaker. Force is inversely ~~pro~~proportional to R and R is proportional to n .

Figure 5.4.9: Student M4's response about the relationship between electronic force and radius

To identify if students could transfer their conceptual model to a graphical model, I asked them to draw a graph showing energy level against Bohr radius. Student M4 sketched his graphical model based on his mathematical calculations and conceptual models.



a) Mathematical relationship between r and n b) Graphical relationship between r and n

Figure 5.4.10: Student M4's mathematical and graphical representations of the relationship between energy level and radius

Both of Student M4's models were constructed based on a step by step conceptual and procedural understanding during the model-based inquiry activities.

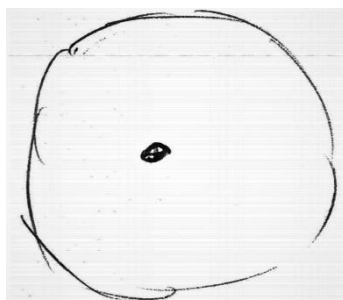
Although he was neither shown nor asked to draw a graph prior to the assessment, he successfully applied his existing models to represent his understanding of the relationship between energy level and radius in a graph. However, he could not do the same when he explained Bohr's assumptions in the post-questionnaire. Although he was able to state all four assumptions in an inter-lesson assessment, he was able to recall only two of them in the post-questionnaire.

M4: I did not remember all four the assumptions, but what I wrote down was that the electrons are in circular orbits which I believe more of a classical assumption, because it is similar to the planetary model with describing centripetal force. The other one is that electrons have angular momentum proportional to the energy level which is just an integer and that's more of them. The angular momentum is a classical physics thing but the integer energy levels are quantum mechanics. So I said it is mixture of the two. And, I still cannot remember the other two assumptions.

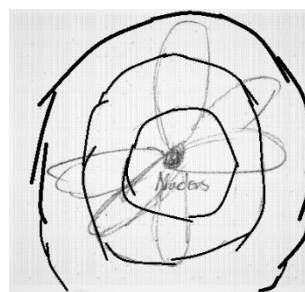
This transcript suggests that even though Student M4 initially learned and was able to recall all four postulates and to differentiate between the classical and quantum ideas behind each postulate, he was only able to retain two postulates and successfully explain by which theories (classical mechanics, quantum mechanics, or a mixture of two) the postulates were influenced.

5.4.5 Lesson 5: Wave Mechanics and the Hydrogen Atom (Quantum Mechanical Hydrogen Atom)

In four weeks, Student M4 changed his model of the atom from a mixed model to more of a quantum mechanical model (Figure 5.4.11).



a) Hydrogen atom model



b) Magnesium atom model

Figure 5.4.11: Student M4's final atom models

Student M4's model of a hydrogen atom (Figure 5.4.11a) indicated that it has a very small nucleus, with one proton, and one electron in a 1s orbital. When he was asked where the electron could be found, he answered, "*somewhere in this sort circular spherical cloud.*" As shown in Figure 5.4.11b, he also sketched a magnesium atom with its orbitals and electron configuration. After student M4 had completed five model-based inquiry lessons, he was able to revise and refine his use of terminology along with his understanding of atomic structure. In the pre-questionnaire, he used some terms like "orbit," "shells," and "orbitals" interchangeably.

M4: So if the atom is not ionized, there are as many electrons as there are protons. The atom can be ionized, in that case would have more or fewer electrons than protons. Umm... the electrons orbit the nucleus at some distance like in the drawing. In higher electron shells I think the orbitals are s, p, d, and f, I think. The orbits are bit more complicated in the higher orbits, but I could not tell you what those are specifically.

Presumably referring to energy levels, he first used the term "shells" and then referred to the same concept using "orbits" and "orbitals." In the post-questionnaire, he demonstrated a sound understanding of the terms and explained atomic structure using more quantum-like terminology.

Student M4's response to the question about electron arrangement in the pre-questionnaire indicated that he had learned about quantum numbers and arrangements but could not remember anything at the time he responded to the question.

I: Have you heard about Lyman series?

M4: I may have heard about it but I forgot since then if I have.

I: Okay. How about principle quantum number?

M4: The same thing.

I: Do you know anything about electron configuration? And how is done?

M4: I remember doing it in the past, but I don't remember specifically how. I could tell you that there are two electrons in the first shell and then 7 in the second. But I don't remember how to specifically show them in specific atom.

I: How about orbital notations?

M4: I don't remember those either.

While Student M4 did not give an answer concerning principle quantum numbers and orbital notation, he did show some (incomplete) understanding of electron configuration. His model seemed to be based on the valence shell model. During a model-based inquiry activity, he calculated the number of electrons in each shell ($n \leq 4$) and related subshells (see Figure 5.4.12).

The 4 th energy level has 4 sublevels called:	- 4f, has 7 orbitals called 4f and can have 14 e ⁻ - 3d, 5 called 3d and can have 10 e ⁻ - 2p, 3 called 2p $\Rightarrow$ 6 e ⁻ - 1s, 1 called 1s $\Rightarrow$ 2 e ⁻
The 3 rd energy level has 3 sublevels called:	- 3d, 5 called 3d $\Rightarrow$ 10 e ⁻ - 2p, 3 called 2p $\Rightarrow$ 6 e ⁻ - 1s, 1 called 1s $\Rightarrow$ 2 e ⁻
The 2 nd energy level has 2 sublevels called:	- 2p, 3 called 2p $\Rightarrow$ 6 e ⁻ - 1s, 1 called 1s $\Rightarrow$ 2 e ⁻
The 1 st energy level has 1 sublevel called:	- 1s, 1 called 1s $\Rightarrow$ 2 e ⁻

Figure 5.4.12: Student M4's calculation table showing orbitals and the related numbers of electrons

The table shows that Student M4 started revising his model of quantum numbers with the first model-based inquiry activity. After this he completed the second activity, in which students engaged with the de Broglie and Schrödinger models of the hydrogen atom. His observational note about de Broglie's model was *"The electron is like a wave instead of a single particle. It absorbs energy (photons) and oscillates at a different radius before it returns back to ground state."* His reasoning after observing Schrödinger's model was *"Instead of oscillating like a wave in the de Broglie model, Schrödinger mode represents it as an electron cloud that changes its configuration when particular energies (photons) are absorbed. No circular orbits in Schrödinger model."* These observations illustrated that Student M4 acquired the essentials of both models and was able to distinguish between the assertions of each model. In his description of the Schrödinger model, he compared the two models in terms of electron transitions and orbital shapes.

$$\psi(x) = A e^{i(kx - wt)}$$

$$p = \frac{h}{\lambda}$$

$$k = \frac{2\pi}{\lambda}$$

$$h = \frac{h}{2\pi}$$

$$\psi(x) = A e^{i(kx - wt)}$$

$$= A i k e^{i(kx - wt)}$$

$$\psi''(x) = A i^2 k^2 e^{i(kx - wt)}$$

$$= -A k^2 e^{i(kx - wt)}$$

$$= -\psi(x) k^2$$

$$\frac{\partial^2 \psi(x)}{\partial x^2} = -\psi(x) \left(\frac{p^2}{\hbar^2}\right) = \frac{\partial^2 \psi(x)}{\partial x^2} (-\frac{h^2}{4\pi^2})$$

$$+ \psi(x) p^2 = \frac{\partial^2 \psi(x)}{\partial x^2} (-\frac{h^2}{4\pi^2})$$

$$p \lambda = h$$

$$k \lambda = 2\pi$$

$$\hbar = \frac{p \lambda}{k \lambda}$$

$$p = k \hbar$$

$$\text{or } k = \frac{p}{\hbar}$$

$$E = \frac{1}{2} m v^2 = \frac{p^2}{2m}$$

Figure 5.4.13: Student M4's derivation of Schrödinger's equation

When Student M4 was asked to derive Schrödinger's equation in one-dimension, he used one of Bohr's postulates about orbital angular momentum, the de Broglie wave equation, the momentum of a photon, and the wave function to find Schrödinger's equation for a free particle (see Figure 5.4.13).

In contrast to his pre-questionnaire response, Student M4 explained in detail, after the model-based inquiry activities, all four quantum numbers and the principles and rules that guide electron arrangement.

M4: Here I was just talking about the quantum numbers. So and the principle quantum number just describes the energy level, just any integer 1 to whatever. "l" is angular momentum number which goes from 0 to n-1 and it also integers.

I: What is that describes?

M4: It is the angular momentum of the electrons. Describes like the shape of the orbital. Like the s, p, d or f just depending... "m_l" is the magnetic quantum number which branches from -l to l. it is also integers. And then "m_s" is the spin which is plus or minus one over two.

I: How do we find which orbital takes how many electrons?

M4: So, orbitals are defined by... the shape of the orbitals defined by "l"s which gives you ... s is 1, p is 2, d is 3, so on... And then each of these shapes has number of electrons depending on... has number of orbitals depending on ... s can only hold two electrons + and - ½. If it is two, then it can have orbitals negative 2 negative... or mess this up sorry. This is zero, this is one, this is two. So, yeah that's just 1 the p orbital can have 6 electrons because there would be -1,0,1, and then + and - ½ in each of those. And d would be 5 orbitals with 2 electrons in each so 10. So...

I: When we made that arrangement, is there anything else that we need to be specifically careful about?

M4: There are the different principles ... just basically about saying quantum numbers of two electrons ... no two electrons can have the same quantum numbers. So...

I: Based on which rule?

M4: It is the exclusion principle. Pauli Exclusion Principle. And then there are two others. I don't remember their name, but one says that like here for example you must fill all empty orbitals before starting to... putting the second electrons with the different spin in the previously filled orbitals. And then the lower energy levels must be filled before higher energy levels are. For example, this orbital [4s]

is filled before these one [4p].

I: Okay. Do you know what orbital means? Shell and sub-shell means?

M4: I think so. The orbitals just shape of the potential location of the electron in the... hmm may be not tough. The shell would be the shape of the location and orbital describes...

I: Sub-shell?

M4: Sub-shell would be like for p would be p_x , p_y , and p_z , I think.

During the think-aloud process, Student M4 was able to define each component that gives us important information about where an electron can be found in an atom. He also talked about particular orbitals and how many electrons can occupy each orbital. Moreover, he identified the Pauli exclusion principle out of all the other principles and rules. Although he demonstrated a sufficient knowledge of the Aufbau principle and Hund's rule, he could not remember their names.

M4: So, this is sort of the question of probability in the macroscopic objects. It is the behavior of all of the sub-atomic particles inside the... like in this table for example they can kind of be averaged out. There may be individual particles that are doing something unexpected, but the vast majority just behave normal. So, there is no unexpected behavior. But in the single sub-atomic particle the behavior cannot be specifically described because of the Heisenberg uncertainty principle which says that the better you know the location, the less you know the momentum vice versa.

In response to a question about why the Heisenberg uncertainty principle does not apply to macroscopic objects, Student M4's reasoning indicated his incomplete model of the principle. He knew that for subatomic particles, you cannot determine both position and momentum, but he said that if all the particles are together, they behave "normal," meaning their behavior becomes predictable. Finally, the transcription below shows one of Student M4's responses from the post questionnaire, concerning wave function, probability density, and Schrödinger's equation.

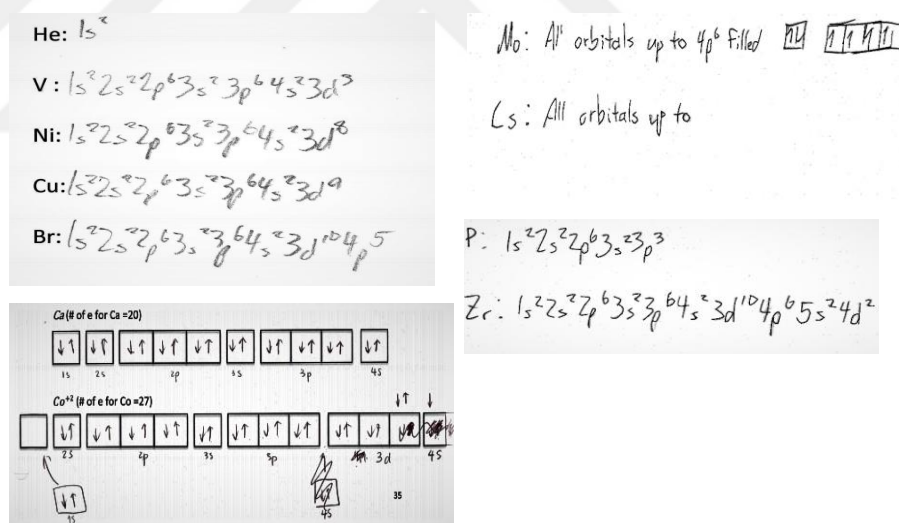
M4: Wave function describes the behavior of electrons as waves mathematically. Probability density... because the Heisenberg

Uncertainty, you cannot know specifically where an electron would be. So the probability density describes where it probably is based on the location in the atom. And then the Schrödinger equation uses the wave function and assumptions of angular momentum to kind of describe the behaviors electrons more specifically.

Student M4's conceptions of wave function, probability density, and Schrödinger's equation were correct, even though his descriptions were very brief and incomplete.

5.4.6 Lesson 6: Multi-Electron Atom

Student M4's conception of electron arrangement was revealed during the pre-questionnaire, inter-lesson assessment, and post-questionnaire (see Figure 5.4.14).



a) Initial model b) Inter-assessment model c) Final model

Figure 5.4.14: The evolution of student M4's electron configuration and orbital notation models

Initially, Student M4 indicated that he did not remember how to represent electron arrangement in an atom. Instead, he just gave a rough definition of how many electrons could exist in the first couple of shells. In an inter-lesson assessment, on the other hand, he was able to represent electron configuration by using all of the principles

and rules correctly. However, he could not demonstrate the same model when he drew orbital notations. In particular, his model showed that he had some incomplete understanding about the Aufbau principle. In the post-questionnaire, he performed better when applying all the rules and principles; however, this time, he also demonstrated confusion between electron configuration and orbital notation representations.

M4: So, instead of drawing all of the boxes, because I did not have time for that, I just said that all of the orbitals up to 4p6. It should be all the way up to Kr. It would be filled with two electrons in each one and then after that would be 5s2 here, and then 4p4 here which gives the total number of electrons. And then for Cs, it would be the similar. It would be all of the orbitals up to 5p6, I think. And then there would be 1 electron in the 6s.

I: Okay. How about orbital notation?

M4: So, for phosphor it is just 1s2 2s2 2p6 3s2 3p3. And then for zirconium 1s2 2s2 2p6 3s2 3p6. It is supposed to be 4s2 3d10 4p6 5s2 and 4d2, I think.

Like Student M2, Student M4's models of electron configuration and orbital notation were interchangeable. While his representations were correct in the inter-lesson assessment, his final models were mixed.

In another activity, students were asked to draw s and p sub-shells with their orbitals. Figure 5.4.15 presents Student M4's drawings of the s and p orbitals from a worksheet.

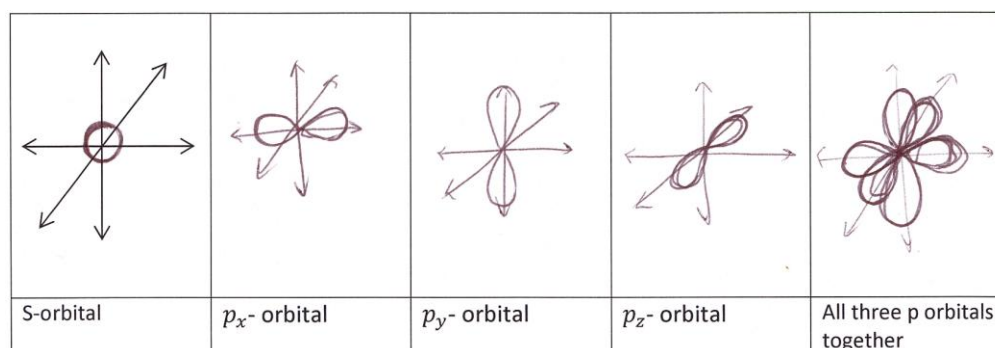


Figure 5.4.15: Student M4's s and p sub-shell and orbital models

In the worksheet, Student M4 displayed an accurate scientific representation of each orbital even though he did not show the probability densities of the electrons' possible locations. Like Student M3, he only showed the probability density when we specifically asked him to draw it in an inter-lesson assessment (see Figure 5.4.16).

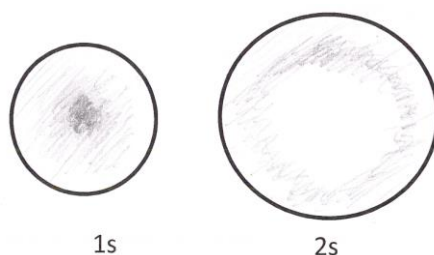


Figure 5.4.16: Student M4's probability density models

Based on Student M4's two models, it is obvious that he developed a scientifically appropriate understanding of probability density in the different sub-shells (1s and 2s). His explanation for his 1s model was "*Electrons are more likely to be close to the nucleus.*" Student M4's probability density representation suggested that one is more likely to find an electron closer to the nucleus. For the 2s orbital, on the other hand, he said, "*Electrons in 2s will probably not be in the 1s shell.*" It is not clear what he meant by this explanation; however, one can assume he was referring to the border of the 1s orbital when he said, "*probably not be in the 1s shell.*" In his drawing, the higher probability area is shown by a circle of darker shading a little further out from the center (normally the 1s and 2s sub-shells are demonstrated as nested circles).

Despite his proficiency with probability density in the inter-lesson assessment, student M4 only drew orbital representations for his hydrogen and multi-electron atoms in the post-questionnaire, without identifying probability density in each subshell and orbital. Furthermore, he demonstrated a good understanding of quantum mechanics terminology

in the post-questionnaire, although he did still show some inconsistencies such as with the terms “*orbital*” and “*shell*” as used in his explanation of probability density above.



6. COMPARISON OF MODELS FROM STUDENTS WHO RECEIVED THE MODEL-BASED LEARNING MODULE VERSUS STUDENTS WHO RECEIVED TRADITIONAL COMPUTER SIMULATION LESSONS

The third research question addressed the comparison of the learning gains and overall progress between the model-based learning module (MBLM) group and the traditional computer-based simulation (TCBS) group during the implementations. All of the participants initially reported having different levels of understanding in three fundamental quantum mechanics topics. Table 6.1 shows students' self-reflections about how much they believed they knew about atomic structure, energy levels, and atomic spectra. Students rated their confidence or knowledge levels on atomic structure, energy levels and atomic spectra concepts. Table 6.1 gives an information about students' meta-cognitive levels as well.

Table 6.1: Students Self-Reflection Report on Their Knowledge about Atomic Structure, Energy Levels, and Atomic Spectra

Student ID	Level of knowledge		
	Atomic Structure (%)	Energy Levels (%)	Atomic Spectra (%)
M1	0	29	0
M2	38	25	21
M3	65	50	41
M4	20	20	40
T1	20	23	0
T2	50	34	35
T3	67	29	23
T4	60	40	0

As Table 6.1 delineates, students felt more confident about atomic structure than energy levels and atomic spectra. Although it appears that the level of knowledge regarding energy levels was below 50%, all students reported that they had basic understanding while for atomic spectra, three students reported “zero” level of knowledge.

Table 6.2 presents students’ initial models prior to study right after the initial screening process. Students’ initial stage of models appears to be different than their self-reflection reports indicate. Students who declared zero knowledge about atomic structure or atomic spectra ended up having either hybrid or quantum-like models/understanding. On the other hand, students who reported above average level of knowledge about atomic structure or average about energy levels showed discrete entity (particle) level models/understanding.

Table 6.2: Students' Initial Models of Atomic Structure, Energy Levels and Atomic Spectra

ID	Atomic Structure	Energy Levels	Atomic Spectra
M1	Discrete Entity (Particle) / Hybrid	Discrete Entity (Particle)	Hybrid/ Quantum-like
M2	Hybrid/ Quantum-like	Discrete Entity (Particle)	Quantum
M3	Discrete Entity (Particle)/ Hybrid / Quantum-like	Hybrid	Quantum-Like
M4	Discrete Entity (Particle)/ Hybrid	Discrete Entity (Particle)/ Hybrid	Discrete Entity (Particle)/ Hybrid
T1	Hybrid/ Quantum-Like	Discrete Entity (Particle)/ Hybrid	Quantum
T2	Discrete Entity (Particle)/ Hybrid/ Quantum-like	Discrete Entity (Particle)	Discrete Entity (Particle)
T3	Discrete Entity (Particle)/ Hybrid/ Quantum-like	Discrete Entity (Particle)	Quantum-like

T4	Discrete Entity (Particle)/ Quantum-like	Discrete Entity (Particle)	Discrete Entity (Particle)/ Quantum-like

Table 6.3 illustrates students' final models at the end of the interventions. After receiving MBLM and TCBS instructions, all students appeared to shift their models toward hybrid, quantum-like or quantum model levels while four students still held on their discrete entity (particle) or hybrid models of atomic structure.

Table 6.3: Students' Final Models of Atomic Structure, Energy Level and Atomic Spectra

ID	Atomic Structure	Energy Level	Atomic Spectra
M1	-	-	-
M2	Quantum	Quantum	Quantum
M3	Discrete Entity (Particle)/Hybrid/ Quantum- like / Quantum	Quantum-like	Quantum
M4	Quantum-like/ Quantum	Quantum	Quantum
T1	Quantum-like/ Quantum	Quantum	Quantum
T2	Discrete Entity (Particle) / Hybrid/ Quantum	Hybrid	Quantum-like
T3	Discrete Entity (Particle) / Hybrid	Quantum	Quantum
T4	Hybrid/ Quantum-like/ Quantum	Hybrid/ Quantum-like	Quantum

Structurally, students' responses in all model categories were fragmented, in the sense that sometimes their ideas and definitions were difficult to connect with one another. Moreover, in most cases students' answers were indicative of different models for the same concepts, which can be placed in different categories. For example, one student might have the idea that an excited electron can stay in the excited state

indefinitely yet the same student might explain emission and absorption phenomena very well or make the connection between spectral lines and electron transitions. Therefore, these students' models were assigned to the hybrid model category unless there was more evidence of a complete model, in which case they were categorized as a quantum-like model. The level of sophistication of students' reasoning carried variations even within the same model category. While some students explained their incorrect reasoning coherently across questions, others' reasoning indicated inconsistencies throughout different questions.

An overall initial and final comparison between the models that students generated from the MBLM group students versus the TCBS group students is presented in Table 6.4. The frequencies of particular models were calculated within each group based on Tables 6.2 and 6.3.

Table 6.4: Frequency of Students' Initial and Final Models

	Model-Based		Traditional	
	Pre-Instruction	Post-Instruction	Pre-Instruction	Post-Instruction
Discrete Entity (Particle) Model	32%	8%	43%	11%
Hybrid Model	36%	8%	19%	26%
Quantum-like model	18%	23%	29%	21%
Quantum Model	5%	62%	5%	42%

Figure 6.1 shows a graphical representation of students' model distributions in both groups prior and after the interventions.

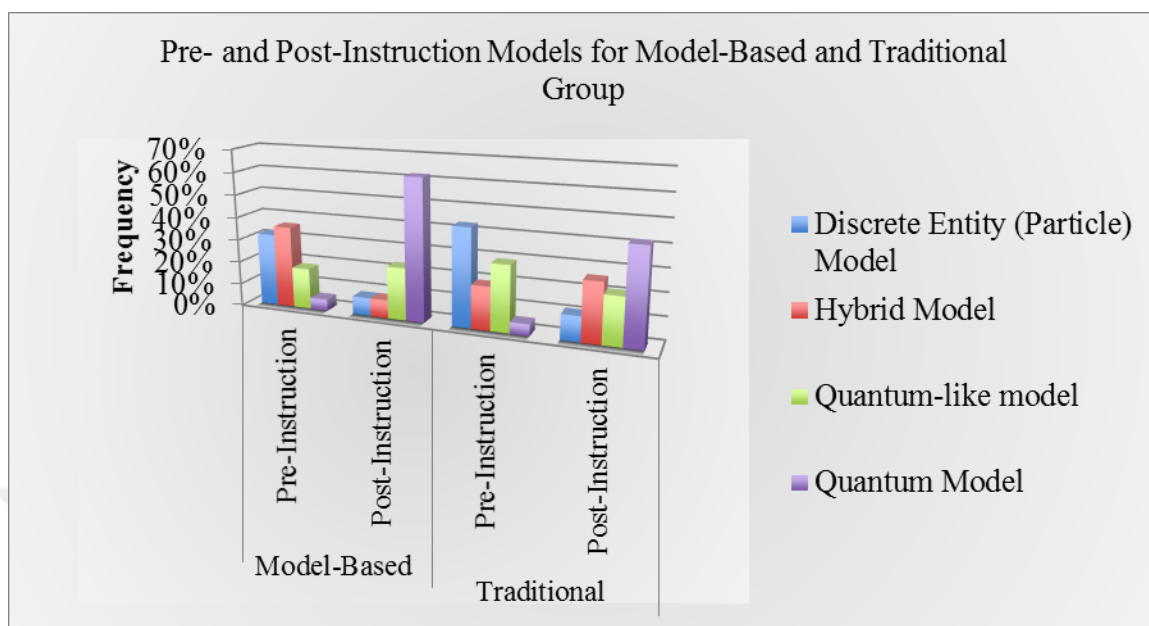


Figure 6.1: Pre- and post- instruction models for MBLM and TCBS groups

An important result that emerged from the pre-and post-questionnaire analysis was that only one student in both MBLM and TCBS groups employed the quantum model in the beginning, but six students shifted their models to the quantum model by the post test. Although there is no significant difference, MBLM students ended up having more quantum and quantum-like models in comparison to the TCBS group. Considering that there were more quantum-like models in the TCBS group and more discrete and entity (particle) and hybrid models in MBLM group, it is fair to conclude that the MBLM helped students to switch their models toward the more scientifically accurate model. Table 6.5 shows the frequency of model change rates in both MBLM and TCBS groups.

Table 6.5: Frequency of Model Change for MBLM and TCBS Groups

	Discrete Entity (Particle) Model	Hybrid Model	Quantum- like model	Quantum Model
Model-Based	-24%	-28%	5%	57%
Traditional	-32%	7%	-8%	37%

As Table 6.5 indicates, MBLM group students ended up having less discrete entity (particle) and hybrid models and more quantum-like and quantum models. Similarly, TCBS group students had less discrete entity (particle) model after intervention. However, they also had less quantum-like model and more hybrid and quantum model (see figure 6.2).

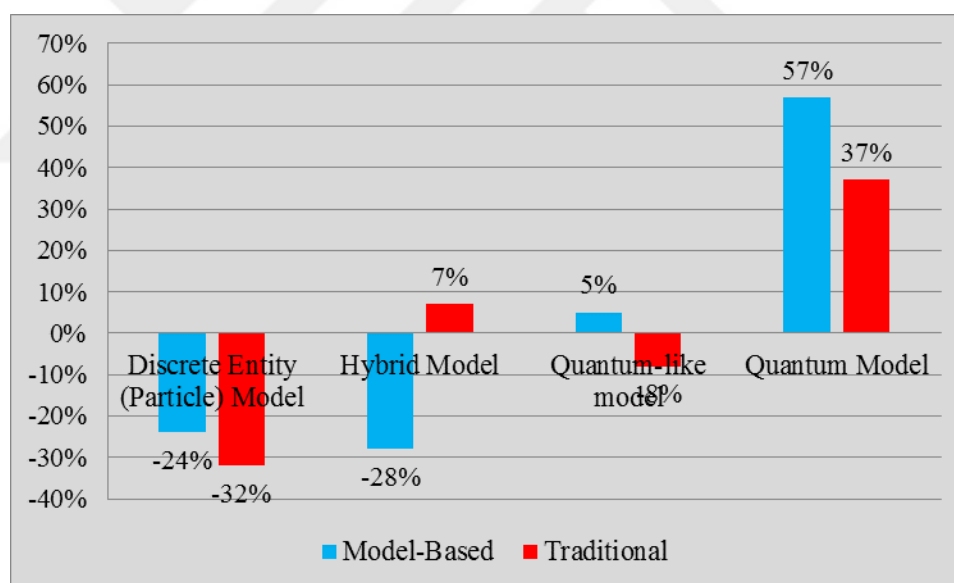


Figure 6.2: Students model improvement graph from pre- to post-questionnaire

Figure 6.2 plots students' model improvement and conceptual gains over the course of the MBLM and TCBS implementations. Students in the MBLM group shifted from their discrete entity models to hybrid, quantum-like, or quantum models (24%) while students in the TCBS group replaced 32% of their discrete entity models with other models. Another significant change happened in MBLM students' hybrid models. 28% of

students' in the model-based group altered their models to the quantum-like or quantum models while 7 % of students in the traditional computer-based group changed their models to hybrid model. After MBLM implementations, students' models were mostly quantum-like (5%) and quantum models (57%). In TCBS group, on the other hand, 37% of students models shifted to quantum model.

6.1 Based on Students' existed models, which type of learning environment is more effective?

Individual differences play an important role in learning and instruction. Every learner filters instruction through a set of individual difference filters or lenses. Individual difference filters may prevent the mental assimilation or accommodation of ideas by the learner. Individual difference lenses will focus the skills and content in ways that will affect how any individual learns. The effects of those differences are universal. (p. viii, Jonassen & Grabowski, 2012)

As Jonassen and Grabowski argues, individual difference and their initial models are a significant predictor for their learning process. Moreover, every individual receives the learning materials based on these differences. Therefore, an analysis was conducted to reveal to what extent students whose models varied from discrete to quantum-like improved their models after both types of learning environments. Figure 6.3 demonstrates model based students' model transitions from pre-questionnaire to post-questionnaire. The analysis showed that 2.5% of student models that were at the discrete entity (particle) level stayed unchanged after intervention. None of them switched from the discrete (particle) model to the hybrid model. However, 8.3% of discrete models were moved toward quantum-like and 12.5% of models were replaced with quantum models.

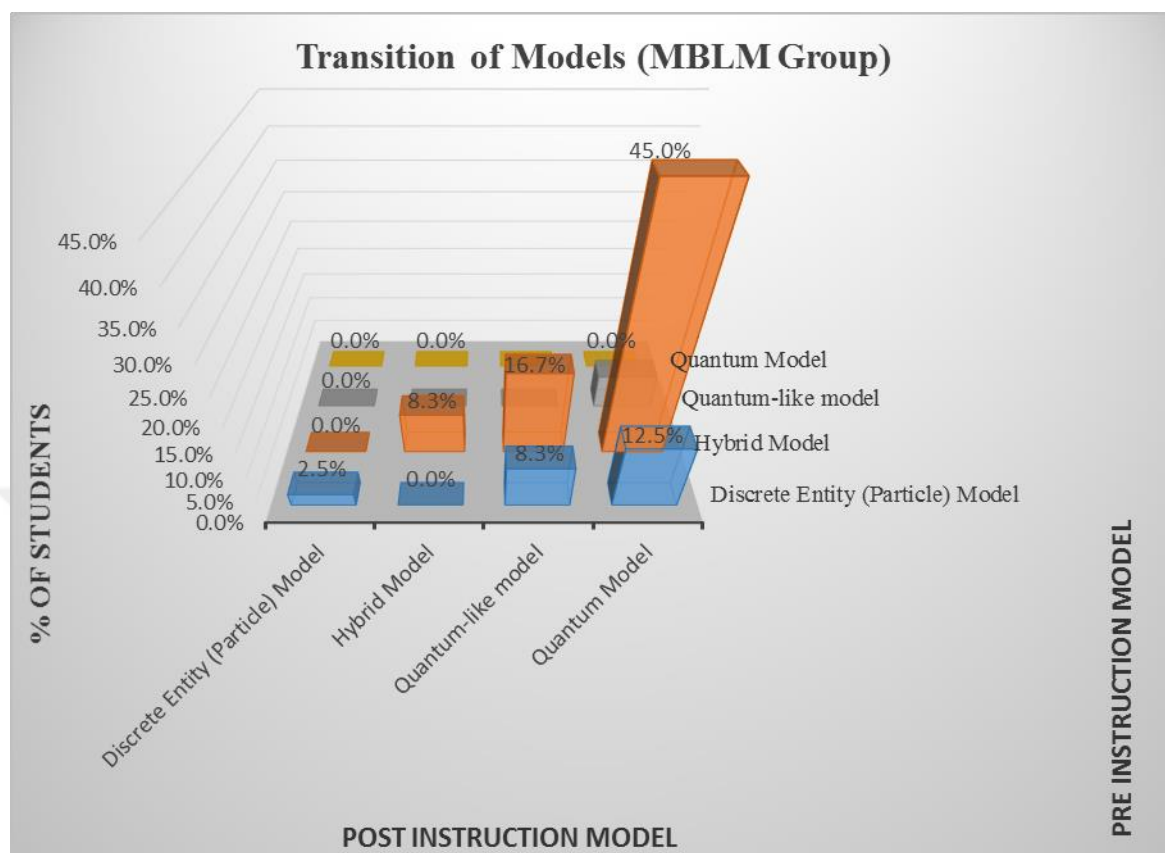


Figure 6.3: MBLM students' model transitions graph

Figure 6.4 presents traditional computer-based simulation students' model transitions between the pre- and post-questionnaire. As is shown in the graph, 15.16% of discrete entity (particle) models were carried on to post-questionnaire. Furthermore, 6.3% of discrete entity models were replaced with hybrid models and the same percentage of the models shifted to quantum-like models. The greatest gain identified in the traditional group was from quantum-like model to quantum model (21.9%).

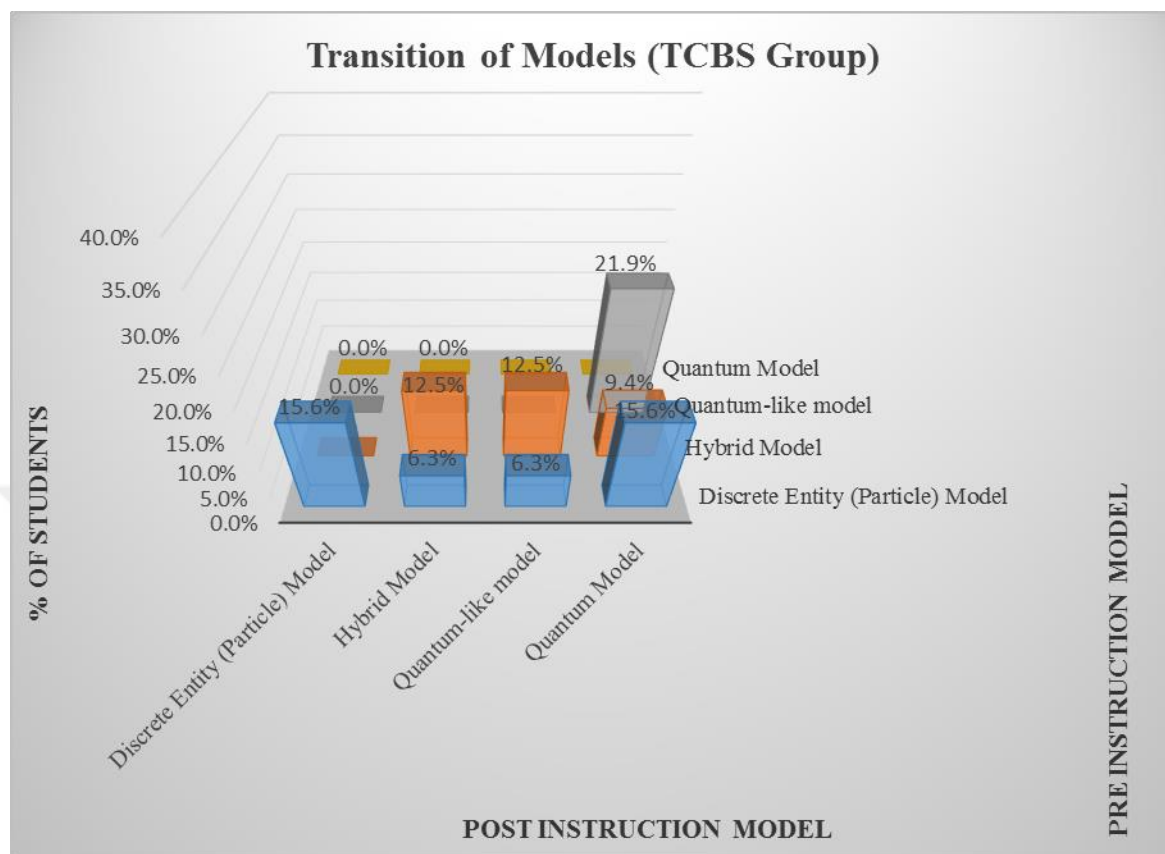


Figure 6.4: TCBS students' model transition graph

These results indicate that even though TCBS instruction appears to be slightly better for the students whose initial models were at the quantum-like model level, the difference between the two treatments was not significant.

The most noticeable difference between the two types of learning environments was seen among students whose models were in the discrete entity (particle) and hybrid model levels before the intervention. As Figures 6.3 and 6.4 indicate, none of the students' hybrid models reverted back to entity discrete models in either type of instructional approach. While 8.3% of hybrid models were kept by MBLM students, 12.5% of hybrid models were carried to the post-questionnaire by TCBS students. The analysis also showed that 12.5% of TCBS students' hybrid models shifted to quantum-

like and 9.4% shifted to quantum models while 16.7% of MBLM students' hybrid models were replaced with quantum-like models and 45% switched to quantum models. These results suggest that students whose models were in the discrete entity (particle) and hybrid model levels gained more benefits from the MBLM instruction in comparison to TCBS instruction.



7. DISCUSSION

In this dissertation study, I have examined freshman and sophomore level physics and engineering students' initial models about fundamental quantum mechanics concepts and their conceptual understanding and model-based reasoning after receiving model-based learning module (MBLM) or traditional computer based simulations (TCBS). Therefore, I presented the qualitative and quantitative analysis of students' representational, verbal, graphical and mathematical models. This study came into prominence in terms of an innovative approach to facilitate students in overcoming their learning challenges and addressing their misconceptions since many studies only focused on common misconceptions that students have in quantum mechanics concepts. In this research, I aimed to provide a model-based learning environment that facilitates students in constructing models in a meaningful way, and evaluating, revising and refining their existing models (Buckley, 2000; Clement, 1989; Gobert & Buckley, 2000). Within the scope of this research, I explored 1) students' initial models of atomic structure, electron's attributions, energy levels, and atomic spectra; 2) MBLM students' model change process starting from prior to the intervention until the end of the intervention; and 3) the pattern of model changes among students who received MBLM versus the students who received TCBS.

7.1 Pre-Instructional Models

Students' pre-instructional models of atomic structure, electron behavior, energy levels/atomic spectra, and use of terminology were examined to understand the common challenges that students carried out from their prior experiences with those QM concepts.

To this end, I analyzed students' conceptual models through both their written depictions and verbal explanations for each question in the pre-questionnaire using constant comparative methods of analysis (Glaser & Strauss, 1965). I found that students' ideas ranged from discrete entity (particle) models up to pre-quantum models.

Research focused on student understanding of different quantum mechanics concepts argues that the classical model of the atom appears to be robustly rooted in students' conceptualization of atomic structure (Akarsu, 2010; Ireson, 2001; Kalkanis, Hadzidaki, & Stavrou, 2003; Ke, Monk & Duschl, 2005; Müller & Wiesner, 1999). In the present study, two of the students' models were identified as classical models of the atom (discrete entity models): the planetary or Bohr model, which has a similar structure to the Earth orbiting around the Sun, and the valence-shell model, which represents the atom in terms of valence electrons using Lewis dot symbols. The findings of this study show similarities with many other studies exploring students' initial atomic structure models. Budde and her colleagues (2002a, 2002b) presented four atomic models that were described by students. In two of the models, electrons were considered as classical particles. These models are exactly the same as the models identified in this study as discrete entity (particle) models except that they called the valence-shell model a spatial-shell model. The other models, where electrons were defined as quantum particles, were named the electronium model and the probability model. In distinction to the study by Niedderer and Deylitz (1998), students in this study did not use 'Electronium' or probability initially in their models. The models identified from the pre-questionnaire were mostly discrete entity models and hybrid models that combine the classical and quantum mechanics perspectives. Petri and Niedderer (1998) and Fishler (1999) argued

that many high school students poses planetary model before taking any modern physics courses. Among freshman and sophomore students, there was only one out of eight students who demonstrated the planetary atom model prior to receiving instruction. While the number of students who used the cloud model was almost one third of the number of students who had a planetary model, and that ratio remained the same after formal quantum mechanics instruction in Fishler's (1999) study, in this study, the orbital-Bohr model (corresponding to the cloud model in Fishler (1999), Müller & Wiesner (2002), and other studies) was the second most common model utilized by students.

An analysis of the data showed that students' models of atoms are mostly incomplete and incoherent even though they had prior quantum mechanics (or modern physics) instruction in high school or at the college level before the study. The results confirm the study conducted by Müller and Wiesner (1999). One interesting point that emerged from students' verbal explanations and visual representations was that although most students were aware of the invalidity of the Bohr model, they could not relinquish depicting and describing that model to represent atomic structure, especially for hydrogen atoms similar to Müller & Wiesner's (1999) study.

The findings also illustrated that students hold scientifically inaccurate conceptions of an electron, including its location, shape, and motion. Their models of electrons were constructed based mainly on determinism and some aspects of classical mechanics. Previous research revealed that students conceptualized electrons as particles (Mashhadi & Woolnough, 1999; Çalışkan, Selçuk & Erol, 2009) or point-like charges (Mannila et al., 2002; Mashhadi & Woolnough, 1999; Taber, 2002). The present study supports such findings and also uncovered more details concerning students' initial

models of electrons including electron as classical wave mode, particle (point-like charge) model, orbiting/zooming model, etc.

The fixed/specific location model and point-like charge model were two common representations among the students, both of which reflect a deterministic perspective. On the other hand, one student (Student T2) represented an electron as a classical wave in his drawing of a hydrogen atom. Although his response to the question about describing an electron included two different representations of an electron (classical wave and particle), he showed some instability in his conceptual model of an electron during the interview. This particular model also emerged in studies by Olsen (2002), Mannila et al. (2002), and Mashhadi and Woolnough (1999), in which participants completed introductory quantum mechanics courses. In quantum mechanics curricula, students are taught about atomic structure (from early atomic models to the quantum wave model), the fundamental particles that compose an atom, and their properties according to a probabilistic framework. Even though students learn that finding an electron in a specific orbital depends on probability distribution and its wave function, they still tend to use a fixed location or specific trajectory model for electron representation, presumably because these are easy to depict and have an eye-catching structure.

Similar studies have shown that the wave-particle duality of electrons seems to be quite a challenging concept for students, even those who complete a formal course in quantum mechanics (Ayene et al., 2011; Fletcher & Johnston, 1999; Johnston et al., 1998; Mannila et al., 2002). In the present study, students mostly used a classical manner of description, as well as combinations of classical ideas with aspects of quantum mechanics. In most cases, until they were asked specifically about electron structure and

behavior, students described a particle model and its attributes. A few students mentioned the double slit experiment (Young's experiment) to define the electron wave function, or Schrödinger's model. However, these explanations indicated an incomplete and fragmented understanding. While none of the students initially acknowledged wave-particle duality as it is, it was also common that an inadequate understanding of the concept led students to model electrons as either purely wave or purely particles, based on type of measurement or observation. They conceptualized that an electron can be either a particle or a wave (not both) depending on the conditions under which you are observing it. The "two independent properties" (either particle or wave) model of an electron was also identified in Olsen's (2002) study, in which a small fraction of students drew an electron as a classical wave, while most students depicted it as a particle with specific properties (location, momentum, mass, etc.).

In another question, students were asked to demonstrate electron configuration and orbital notation. None of the students indicated a complete understanding of both. While a few students could recall and write down electron configuration information, all attempts to use orbital notation were incorrect. In fact, students could not remember how to represent orbital notation. This finding is a unique feature of this study as there are no sufficient findings in the current literature concerning students' understanding of electron configuration and orbital notation.

To identify whether students were unable to relinquish their classical way of perceiving atomic structure because they did not understand quantized energy levels and atomic spectra or whether, despite knowing these concepts, they could not make the connection between atoms and quantization, students were asked to describe and

represent their models of energy levels and atomic spectra. The concept of quantization carries great importance as a key idea in the transition from classical thinking to quantum theory. The interview results revealed that students could not relate electronic transitions with the concepts of orbitals, shells, and sub-shells as parts of a meaningful understanding. This finding seems to be consistent with Taber's (2002) study of college students.

Several challenges and misconceptions were identified in students' representations of energy levels and atomic spectra. The definition of quantization seemed to have been acquired by all students; however, it appears that they had difficulty transferring that knowledge to explain the atomic spectrum.

The quantization of energy levels and electronic transitions were found to be the two concepts around which students in the present study most commonly developed hybrid models. Students built their models of these concepts around the context, as found in studies by Bao (1999), Bao and Redish (2006), Didiş, Eryılmaz and Erkoç, (2014), Hrepic, Zollman, and Rebello (2010), and Wittmann, Steinberg, and Redish (2003). In this, students showed the incoherency of their models of quantization and electronic transition between different questions. While students mentioned that any transition is possible for electrons during absorption and emission, they claimed, in another question, that electrons must always jump back to the ground state when losing their energy to stay in the most stable state. A similar non-scientific model was also identified in Zollman, Rebello, and Hogg's (2002) study, in which students drew energy levels and transitions that either started and ended at the same energy level, or that ended at the lowest energy level.

In Didiş and her colleagues' (2014) study, the researchers examined students' models of quantization and energy levels. They found that students built different models of quantization and angular momentum. Taber (2002) also identified students' difficulties with energy levels and quantum numbers. The research revealed that students had difficulty labeling orbitals and their attributions (such as shape, coordinates, etc.). Students' representations of quantum numbers for specific elements indicated that the order of orbitals and the occupancy of electrons were quite vague concepts. This research supports such findings and fills in some of the details of how these students struggled to conceptualize energy levels, quantum numbers, electron configurations, and orbital notation. None of the participants in this study recalled how to represent orbital notation. Although three of them illustrated a fragmented understanding using quantum numbers to write electron configurations, these were not scientifically complete.

Previous research has suggested that the connection between electron transitions (transitional lines) and atomic spectra may not be easily seen by college students (Didiş, Eryılmaz & Erkoç, 2014; Rebello & Zollman, 1999; Zollman, Rebello, & Hogg, 2002). A considerable majority of the students could not explain the dark lines observed in the sun's atmosphere caused by atomic absorption, although they could individually describe the absorption and emission phenomena. Additionally, they conceptualized absorption and emission as two separate cases; emission does not have to follow absorption.

A closer analysis of students' responses indicated that incomplete models led students to use wrong or mixed terminology to describe quantum mechanics phenomena. As found in Taber's (2002) study, students were confused about the use of certain terminology, such as shell, sub-shell, orbit, orbital, and probability density. In most cases,

students showed discrepancies in their use of words when they defined atoms, electron position, and atomic spectra. The results of this study, along with current literature, suggest that if the essential concepts, which are called the “threshold” (Cousin, 2006; Meyer & Land, 2003, 2006; Park & Light, 2009), are not completely understood by learners, their construction of models ends up being incomplete and incoherent, hindering the learning of further, more complex concepts (Park & Light, 2009).

7.2 MBLM Students’ Model-Chance Process

In order to monitor students’ model change, I carefully investigated each model-based inquiry student’s model revision process. To this end, I tried to examine the MBLM students’ atomic structure, energy levels, and atomic spectra models from the pre-questionnaire to the post-questionnaire, including their worksheets and inter-lesson assessments, by using the Clement (2000) framework, and I analyzed their work by using multiple case study analysis (Stake, 2013). During the analysis, I investigated each individual case separately, but kept all the cases in mind. As a result, I found that the model-based inquiry lessons worked to different degrees for each individual. In general, all four students revised and refined their models to some degree. While two out of three students approached the target level models by the end of the study, one student kept using hybrid level models. Providing the students with a learning environment supported with different scientific models facilitated their evaluation of their own models, allowing them to revise and refine them if necessary to approach accepted scientific understanding (Lehrer & Schauble, 2000; Nersessian, 1999; Raghavan & Glaser, 1995).

The analysis showed that all the students in the MBLM group except student M3 started with a hybrid atomic structure model in the pre-questionnaire. This means that

they believed that atoms include circular paths on which electrons are located, but also stated that electrons travel in unknown paths around the nucleus. Student M3's model was a discrete entity (particle) model that indicated that electrons have fixed locations and that more than one electron can travel on the same circular path around a nucleus. These findings were very similar to many other studies revealing student understanding of atomic structure (Harrison & Treagust, 1996; Justi & Gilbert, 2000; Ke et al., 2005; Muller & Wiesner, 2002). However, in contrast to Harrison and Treagust's (1996) study, four students mentioned that they were aware that their models of the atom were not reflecting the scientifically appropriate atomic model. Students said that they used their models, which looked like the Bohr model, for the purpose of easy representation.

In order to help the students construct a sturdy foundation for their models of atomic structure, model-based inquiries were designed to demonstrate the weak and strong sides of early atomic models (Irwin, 2000; Niaz, 2016). Although early atomic models are included in middle and high school chemistry and physics curricula, most students did not know how the theories developed or anything about the experiments and results upon which the early scientists based their theories (Justi & Gilbert, 2000). After the students completed all the model-based inquiry activities related to early atomic models, they were able to talk about the aspects that each model was able to explain or clarify about observed phenomena and what aspects they failed to explain. With the planetary model simulation, students also observed and discussed the circular motion of electrons by referring to Maxwell's electromagnetic wave theory. Eventually they realized that an accelerated electron would lose its energy during its circular motion and eventually collapse into the nucleus. The sequence of activities and the critical thinking

process led students to reconcile their models of the atom with quantized energy levels (Roblee, Garik, Abegg, & Zollman 1999).

Most students were not unfamiliar with the concept of energy quantization. Almost all of them had at least a basic understanding that electrons can only take certain energies and be on certain energy levels, not in between. While three students demonstrated quantum-like models of energy levels prior to the study, five of them had incomplete or inaccurate models. In Taber's (2002) study, it was presented that students had difficulty connecting the quantization of electrons with atomic structure. Furthermore, these students found it a conceptual challenge to master the terms "*shell*," "*sub-shell*," and "*orbital*." The present study confirms these findings and reveals that the students' inaccurate models caused them to struggle to learn the principals of quantization. Prior to the study, students used the terms "*orbital*," "*orbit*," and "*shell*" interchangeably. After the MBLM lessons, some concepts (e.g. orbit, sub-shell) became familiar, but other terms like "*shell*" and "*orbital*" were still unclear to the students.

Some common mistakes made by the students were about electronic transitions. First, they did not remember how to calculate the energy, wavelength, and frequency of a photon released during a transition. Consequently, one of them could not remember the relationships between these three phenomena. After they completed the model-based inquiry activities, which were supported by computer simulations as well as by mathematical and physical models, the students were able to confidently state the relationships and calculate photon energy, wavelength, and frequency in an inter-lesson assessment and the post-questionnaire.

Another inaccurate idea was that ground state is always the final destination for every excited electron, independent of their initial energy state, and/or that an electron follows an order when it jumps down energy levels. The energy level simulation appeared to facilitate the students in revising and refining their inaccurate models. In the final interview, they demonstrated a conceptual understanding at the target model level.

Energy levels and atomic spectra are two important concepts that construct a bridge between early atomic models, the Bohr model, and quantum theory. Therefore, the model-based inquiry activities were designed to help the students to conceptualize these concepts in an organized way and to refine their models. Initially, students were able to explain the absorption and emission phenomena but three of them conceived these two phenomena as being independent from each other. They believed that an excited electron could stay in the excited state indefinitely. Furthermore, as in the findings of Zollman, Rebello, and Hogg (2002), two students initially illustrated incomplete models and could not make the connection between electron transitions and atomic spectra. However, engaging with model-based activities helped students to alter their unscientific models. In the post-questionnaire, all the students except student M4 showed evidence that they were able to transfer their models of electron transitions to explain absorption and emission spectral lines.

Many researchers arrived at a consensus that the Bohr model of the atom is the most predominantly assimilated model among students from middle school to college level (Cros et al., 1986, 1988; Mashhadi, 1994; Petri & Niedderer, 1998; Taber, 2002; Tsaparlis, 1997). This study supports such findings as well as claiming that it appeared that the students were only familiar with Bohr's atomic representation prior to the study,

not any of the postulates that led him to his theory or the mathematical representation of the radius of each energy level. None of them could answer a question in the pre-questionnaire that asked about the first three spectral line series (the Lyman, Balmer, and Paschen series). Two of the MBLM activities addressed the derivation of the Bohr radius and Bohr's assumptions. Unfortunately, spectral line series were introduced to students in the traditional way since there was not a specific model-based activity for them. In the post-questionnaire, most students indicated a good understanding about Bohr's postulates and, most importantly, they were able to transfer their understanding to sketch a graph of energy against radius, something that was not shown or discussed during the model-based inquiry activities. This was a sign of a meaningful conceptual understanding as the students could use their verbal, mathematical and graphical models interchangeably.

Mathematical representation and the models for the calculation of electron behavior were very complex and difficult for most of the students. In particular, solving the Schrödinger equation for higher energy levels and orbitals was quite challenging (Tsaparlis, 1997). Schrödinger's equation produces three quantum numbers which give us an idea about how electrons are arranged in an atom (Ward & Volkmer, 2006). Hence, one of the model-based inquiry activities was designed to show a simple derivation of Schrödinger's equation and to simulate how the early scientists brought their classical knowledge into a quantum perspective to solve electron wave function. In order to prevent any complications or discouragement, I encouraged the students to use their knowledge of electromagnetic wave equations and the fundamentals of relativistic theory (Ward & Volkmer, 2006). This derivation activity gave the students an opportunity to use, in a scientific context, some quantum terms such as wave function, probability

density, and the Schrödinger equation itself. Consequently, they revised their scientific terminology from what they were using in the pre-questionnaire.

All the students who completed the MBLM activities were able to demonstrate a scientifically accurate representation of probability density in the 1s and 2s orbitals. Moreover, three of them were able to describe probability density and one of them gave a complete definition of what Schrödinger's equation and wave function tell us.

The Heisenberg uncertainty principle appeared to be a very familiar concept as students were mostly able to describe it, even prior to the study. In the post-questionnaire, one item aimed to examine whether their conceptual understanding of the uncertainty principle was complete and meaningful. Unfortunately, only one student gave a scientifically appropriate answer, stating that the uncertainty principle applies to all objects but in the macro state it becomes insignificant in comparison to its effect at the sub-atomic level. The other two students stated their reasoning but could not accurately explain it.

Based on a close reading of students' responses in the pre-questionnaire and on discussions during the implementation, it appeared that the students tended to recall their knowledge of chemistry (high school or college level) when they explained atomic structure and electron arrangement. Almost all the students talked about the number of electrons that can be found in each shell, but as Taber's (2002) findings indicated, they failed to identify electron configurations or use orbital notation by referring to quantum numbers. One whole lesson was devoted to understanding and working with electron configuration and orbital notation. The quantum numbers physical model was received very positively among the students. By working as group, they had a chance to discuss

and correct each other's ideas. As a result, all the students who completed the MBLM activities and took the post-questionnaire illustrated a sufficient understanding of quantum numbers and electron arrangement in an atom. Moreover, they expressed a good understanding of the Pauli principle, Aufbau's principle, and Hund's rule in their electron configurations. However, the orbital notation and electron configuration concepts still appeared to be very confusing for students. Half of the students either could not use orbital notation or mixed the two representations.

As in Niaz et al.'s (2002) findings, students in this study were able to construct a plausible and coherent conceptual understanding of scientific progress after they completed the model-based inquiry activities in addition to discussion and argumentation. However, as other researchers claimed, the students tended not to completely abandon their old models even though new models were introduced (Coll & Taylor, 2001; Coll & Treagust, 2003; Ke et al., 2005). They preferred to hold on to the simplest and more common ideas such as the Bohr model and the particle model of electrons, even though deep down they know that these models do not represent actual scientific facts.

7.3 Comparison the Benefit of Using MBLM Versus TCBS Instruction

In chapter 6, I analyzed the initial and final models of the students in the model-based learning module group versus the traditional computer-based simulation group and compared the level of their model transitions from pre-questionnaire to post-questionnaire. Several educational researchers claim that as a result of different ways of thinking and experiences, students may hold many alternative conceptions of science concepts (Gilbert, 1983; Pfundt & Duit, 2000; Tobin & Fraser, 2003; Treagust, 1988). Similarly, in this study, I found that students' initial and final models from both groups

contained many inaccurate models (discrete entity or hybrid) of fundamental quantum mechanics concepts. All participants in this study completed either MBLM or TCBM with considerable levels of engagement; however, some fragmented conceptual understanding and models remained. The results of this study are a supplement to many other studies' findings that the behavior of sub-atomic particles is a difficult concept to fully conceptualize (Olsen, 2002; Singh, 2001; Singh et al., 2006; Singh, 2008a, 2008b; Wittmann et al., 2002). Similar to Micheline and Stefanel's (2008) study, physical models (hands-on activities), visual models, and mathematical/graphical representations affected the evolution of each individual's model toward the more scientifically accurate quantum model even though some models ended up in the hybrid model category at the end of the MBLM implementation.

Like the results from the model and non-model group students in the study by Stull et al. (2012), the analysis of this study showed that students who received model-based instruction are more likely to switch their models to quantum-like and quantum models than students who received traditional computer based simulations. A detailed analysis of the effects of both types of instruction on students' model transition indicated that students in either group who were in the discrete entity model and hybrid model stages prior to the interventions gained significant conceptual understanding in MBLM group. Therefore, novice students can gain benefits from model-based inquiry activities to refine their models toward quantum-like, or quantum models. Considering that many high school and undergraduate students have models that either reflect a purely classical mechanics perspective or a mixture of classical mechanics and quantum mechanics, the finding of this research can have significant applications in both high school and even

college level modern physics curriculum. Both types of learning designs were able to stretch quantum-like model level students' conceptual understanding beyond their initial understanding. These findings can be understood using the “zone of proximal development” (ZPD), which indicates the difference between how much students are able to improve on their own versus with the help of supported learning materials (Vygotsky, 1978a, 1978b; Wood et al., 1976).

One of the problems that might affect the overall benefit of model-based activity was that the quality of the engagement with the models was not the same for all the MBLM students. While three students in MBLM appeared to be very motivated and excited to examine new models, follow the instructions, and engage further (e.g., asking questions, inquiring, discussing) to glean as much as possible from the model-based inquiry activities, one student indicated a lack of motivation and interest toward the models they used during the activities. Their focus was on completing the activities without any extra effort. Those students who did not use models effectively and mindfully could not improve their models as much as students who engaged with the activities and thought critically through the rationale behind their model. Stull et al. (2012) claimed that just observing a model is not enough for a successful performance. Unless learners are guided in recognizing the alignment between models and scientific phenomena, it appears that model based activities are not effective in facilitating model change and improved conceptual understanding. Similarly, students who highly engaged with the discussions, argumentations, and models during the model-based inquiry activities were more likely to make model transitions toward the targeted models.

Although the control group students who engaged with traditional computer-based simulations indicated some model transitions between the pre- and post-questionnaires, their reasoning was not as sophisticated or complete as the MBLM group students. This study confirms the argument brought up by Zollman (1996) and Jaakkola et al. (2011) that computer simulations do not provide an effective learning environment for students to construct meaningful conceptual understanding unless it is supported with a well-structured learning design. Stull, Barrett, and Hegarty (2013) argued that if the essential and tactile differences were ignored between visual models such as computer simulations and physical manipulatives, then both learning tools have the same effect on student performance. In this study, it was shown that virtual models facilitated students' conceptual gains to some extent. However, after a certain level, students who used different types of models with hand-held interfaces, outcome observation, graphical and mathematical representation, and manipulation developed the actual conceptual understanding and scientific reasoning that helped them transfer knowledge between different concepts. In another study, Stull and Hegarty (2016) suggested that the combination of virtual and concrete models was more effective for improving students' performance than virtual or concrete models alone.

Constructivist learning theory advocates that individuals' conceptual development can occur only if they actively engage with learning materials and take responsibility for their own learning (Bransford et al., 1999; Dewey, 2007; Mayer, 1996; 1999). Therefore, researchers have attempted to develop a more effective way of helping students conceptualize science concepts. Due to the nature of quantum mechanics concepts, it is more challenging for educators and researchers to develop a learning environment that

enables learners to make the conceptual switch from a deterministic to a probabilistic view. For this reason, model researchers have been considering both how to deliver the science conceptions accurately and how to facilitate visualization/manipulation of real and abstract phenomena. The First with Science Curriculum Improvement Study (SCIS) developed at the University of California, Berkley in 1961 (Karplus, 1964) and Karplus (1977) initiated attempts to use “concrete reasoning patterns” in a learning cycle, which were grounded in Piaget’s theory. Later researchers developed these ideas and designed instructional units supported with different models, similar to the initial studies.

In this dissertation study, models were implemented in a well-guided but non-lecture based instructional design that used only visual, physical, or graphical models. Students doing the model-based inquiries were supported with guided instruction where they were encouraged to use their reasoning to make connections between different types of models including their existing models. Furthermore, since model use can also be risky in terms of triggering new misconceptions of inaccurate models, students were taught to recognize the limitations of the models and in what sense they were not accurately representing the real phenomena.

7.4 Implication for Physics Courses and teaching/learning physics

The findings of this study have important implications for any science-related educational curriculum design. The analysis in this study and other contemporary studies indicated that students have difficulty translating between conceptual, representational, graphical, and mathematical understanding in quantum mechanics concepts due to their complex, probabilistic, and abstract nature (Bethge & Niedderer, 1996; Fanaro, Otero, & Arlego, 2009; Griffiths & Preston, 1992; Johnston, Crawford, & Fletcher, 1998; Singh

2001; Wittmann, Steinberg, & Redish, 2002). Interpretation and understanding of abstract quantum mechanics concepts become easier and more scientifically appropriate with the use of different types of models (e.g., physical, visual, graphical, mathematical). The use of models provides learners the opportunity to manipulate and investigate phenomena that are difficult to visualize as part of a mental process. Additionally, students' attitudes toward using different models were also highly positive. Based on exit-questionnaire responses, almost all MBLM students found the model based activities fun and useful, although they felt some of the activities were too long and insignificant in terms of being a conceptual resource. Below are some responses from students in both instructional groups from the exit questionnaires:

Q: What part of the learning activity helped you the most on your learning? Why?

M3: Physical models $\Rightarrow$ I knew the things that derived from them already, but figuring it out on my own as if I knew nothing is actually more rewarding (After early atom models lesson)

M3: Asking me questions (prompting me to think on my own instead of telling me). Since I got some questions wrong, I am more inclined to remember that we discussed about these questions (After planetary model lesson)

M2: The calculation, because it made the concept more tangible and more real since it can be expressed in numbers. (After planetary model lesson)

M4: The calculation of energy levels and comparing the results to simulation results helped show relationship. (After energy level lesson)

M4: Using the spectrometer and guessing the element showed practical application. (After Atomic spectra lesson)

M3: Simulation $\Rightarrow$ excellent visualization; however, left me wondering why the shape is different & what decides which energy is emitted?? (After Atomic spectra lesson)

M2: Deriving the equation, to see connections between concepts (After Bohr atom theory lesson)

M3: The discussion and visualization of the equations $\Rightarrow$ deriving on our own. (After Bohr atom theory lesson)

M3: Physical model. I had a difficult time understanding the relationship between the orbitals previously. (After quantum wave model lesson)

M4: Derivation of actual formulas was most helpful for understanding the reasons behind certain ideas. (After quantum wave model lesson)

M2: Electron configuration model. Visually understand how the electron orbits fill up. (After multi-electron model lesson)

M3: Physical model (one with toothpicks) and the balloons. The toothpick one had very clear lay out – it was easy to see the relationship. The table that shows with orbital gets filled first (After multi-electron model lesson)

M4: The balloons were helpful for visualizing orbital shapes. (After multi-electron model lesson)

The MBLM as a whole instructional unit addressed different students' learning needs by providing reading, virtual, and physical models; mathematical and graphical components; and group discussions. Between physical models, simulations, derivations of equations, and discussions, students seemed to appreciate physical models and discussions most. Particularly, some physical models appeared to be quite intriguing and remarkable to students. For example, students enjoyed engaging with the physical model of electron configuration and black box which represented potential energy in different energy levels. They also liked early atom physical models (foam balls) and balloons which were used to show orbital shapes. Those activities worked as expected with

MBLM students in terms of acquiring the essential physics content understanding. I believe the reason that these physical models were received well by students was because they simply simulated very complex and abstract phenomena. The electron configuration model in particular gave students an opportunity to see how shell numbers were connected to sub-shells as well as other quantum numbers including electron spin. Normally, students learn these concepts by calculating and writing down the notations. With this model, they played with beads and a configuration platform like they played with Legos. The balloon model gave them an opportunity to create different orbitals and make an observation in 3D. However, atomic spectroscopy activity appeared to be very time consuming for the students. Two students commented that the activity needed to be shortened with less observations of few gases, because after couple observations they felt it repetitive. Therefore, it is important to keep model-based inquiry activities short and comprehensive for more fruitful engagement.

Virtual perspectives from the simulations seemed to help students who had difficulty visualizing quantum mechanical phenomena. When designing the MBLM, I tried to include the simulations which I thought they could be an effective support students model construction process. Both TCSB and MBLM students find *Hydrogen Spectroscopy* developed by the group at Kansas State University (Escalada, 2001; Escalada et. al., 2004; Zollman, et al., 2002), *Energy Levels and Photon Absorption of Hydrogen Atom* developed by astronomy education group at the University of Nebraska, *Atomic Absorption and Emission* developed by Cengage Learning and PhET computer simulation for *Laser* and *Neon Lights & Other Discharge Lamps* simulations developed by University of Colorado Border (McKagan, et al., 2008; Perkins, 2012; Wieman et al.,

2008). These simulations were the only ones which allowed students to do some level of manipulation and observation based on different input. I assume students liked these simulations because they had a chance to actively engage with them rather than just observing the animated phenomena. In fact, some simulations such as the PhET Hydrogen Atom (particularly the Classical Solar System) and Bohr Model developed by McGraw Hill Education seemed to be least favorable simulations due to the limited user interactions. This result suggests the necessity of new computer-based simulations which should provide more insights and active engagement.

Mathematical models which were a significant components of model-based inquiries in quantum mechanics were received differently by each student. Since the subjects of this study consisted of mostly freshman and a few sophomore students, I tried to include very simple mathematical models which required mainly algebra but a little calculus. Most derivations were done by using classical mechanics equations which presumably students were already familiar with. Based on students' responses and my field observations, I found that the students who had a strong background in calculus found the mathematical models very useful to support their conceptual understanding. However, one student (Student M1) had difficulty to solve spectral line series and energy-frequency-wavelength equations to find wavelengths, and two students (Student M3 and M4) found quite difficult to solve Schrodinger Equation and remember it later.

Overall, for instructors who intend to teach complex physical phenomena such as quantum mechanics, MBLM facilitates the learning of as many students as possible.

T4: The discussion part clears up the misunderstanding that I had.

T3: reading, today's reading part is very helpful in explain the way the model works and why there are flaws above it. (After Bohr atom theory lesson)

T4: Having the discussion after the reading helped solidify my understanding. (After quantum wave model lesson)

T3: Comparing the particle and wave models helped me understand why an electron is not just a wave. (After quantum wave model lesson)

T1: The discussion that followed the reading made things more clear. (After multi-electron model lesson)

T2: Discussing and working through the questions, doing this can put all the info we read in the book together. (After multi-electron model lesson)

While two of the traditional group students frequently talked about how reading parts of the book were useful for their understanding, two of them, who were English as a second language students, found the reading long and unclear. Although the traditional group discussed very little before and after each lesson, all of them mentioned how useful the discussions were in comprehending that week's topic. The number of students who pointed out the computer-based simulations as helpful was few in comparison to the other two components (reading and discussions).

I also asked students for their ideas about the challenging parts of the learning activities or lesson itself. Their responses are shown below:

Q: What is still the most challenging part and why?

M4: Nothing was particularly challenging (After early atom models lesson)

M3: Trying to come up with original points (pretending to know nothing) $\Rightarrow$ but this is very helpful (After early atom models lesson)

M4: Nothing was incredibly challenging (After planetary model lesson)

M2: Today's computer simulation was a little bit more confusing than from last session. (After planetary model lesson)

M4: I can't quite distinguish between the types of series easily. (After energy level lesson)

M1: The simulation b/c it was confusing at first. (After energy level lesson)

M2: Remembering the names of the series because the names don't relate to concept, so it's hard to remember. (After energy level lesson)

M4: Equations for series are difficult to remember (After Atomic spectra lesson)

M3: The physical model was difficult to take data and did not seem as helpful/ useful as simulation did. (After Atomic spectra lesson) (After Bohr atom theory lesson)

M3: I found it difficult to understand the concept this lesson. The simulation did little to no help to my understanding. (After Bohr atom theory lesson)

M4: I don't completely understand the Schrödinger equation because I do not completely understand the wave function. (After quantum wave model lesson)

M3: Understanding why this happens, and the property of spin- but I think I need more knowledge to go in depth. (After multi-electron model lesson)

The number of students who found the learning materials or activities challenging was quite low in the MBLM group. However, there were a couple remarks focused on certain computer-based simulations such as the planetary model, energy levels, and Bohr model simulations as well as some physics topics such as spectral series, the Schrodinger equation, and wave functions. Sometimes students commented about the lack of usefulness of some computer simulations because of limitations in conceptual deliverables. Unfortunately, it is difficult to find comprehensive simulations with manipulatives for some of these quantum concepts. Except for the energy level simulation, all of the simulations mentioned by students were demonstrative rather than

manipulative. Most do not go beyond giving students an excellent visual aid. Therefore, students who had hybrid or higher level initial models thought these simulations were a waste of time. The other most frequently stated challenge involved certain concepts such as the spectral line series and their equations, Bohr's postulates, the Schrodinger equation, and wave functions. Since these concepts are descriptive and require some level of memorization, students could not fit these concepts into the model-based inquiry activities. That is, they expected all concepts to come with some sort of physical model, simulation, or graphical representation that would help them engage with and retain the idea behind the modeled phenomena. Due to the unsuitability of some topics for model-based activities, the MBLM included some topics (except the Schrodinger equation) that we only discussed and solved a few questions for. Therefore, most students complained that it was difficult to recall the titles of these concepts, which were named after the scientists who introduced them. Although the Schrodinger equation activity included the integration of new quantum entities into the classical mechanics energy formula, one student, (who may have had low mathematic skill or interest) found the derivation was difficult and not helpful to their understanding.

T4: I was somewhat confused about the part in the article that talked about centripetal force for the electrons around the nucleus. (After early atom models lesson)

T2: Reading, I read slow and there are a few new vocabularies for me (English is my second language) (After early atom models lesson)

T1: I am a bit shaky on the explanations as to why Rutherford's theory is wrong. Math would [have] helped. (After early atom models lesson)

T1: The most challenging part is understanding why electrons lose energy when they accelerate. (After planetary model lesson)

T3: I still do not fully understand the behavior of electron particle-waves.
(After planetary model lesson)

T3: I am still unsure of some of the calculations and mathematics involved.
(After energy level lesson)

T1: The calculations aren't very intuitive yet. (After Atomic spectra lesson)

T3: I don't fully understand how to calculate energy, wavelength, etc.
(After Bohr atom theory lesson)

T2: Understanding why Bohr's model doesn't work with atoms except hydrogen
(After Bohr atom theory lesson)

T1: Without math, much of this is difficult to visualize. (After quantum wave model lesson)

T3: Visualizing the shapes for high-level subshells is difficult. (After multi-electron model lesson)

In the exit questionnaire, all students in the TCBS group responded to the above question with at least one or more complaint(s). As mentioned earlier, reading the textbook was one of the biggest challenges for the students. Without any connection or further discussion, students claimed that they became more confused after reading some of the sections in the book. Although there were some mathematical equations and derivations in the book, students said they were not useful unless the students did the derivations by themselves.

Overall, even though students in both groups had very different models at the beginning, the model-based learning module appeared to improve all students' conceptual understanding of and attributions toward quantum mechanics concepts, bringing them closer to the targeted level. However, traditional computer-based simulation students' conceptual understanding and attributions seemed to vary after completing the lessons. In other words, while the learning materials seemed to be very

useful to some of the students, it did not help others as much as the rest. Based upon these findings, I conclude that instructors who have a very diverse group of students would benefit from model-based inquiries in order to address every individual's needs and learning pace.



8. CONCLUSION

8.1 Students Initial model about fundamental quantum mechanics concepts

In this thesis, I first discussed the exploration of freshmen and sophomore students' initial models regarding atomic structure, electron attributes, energy levels, and atomic spectra. Students' models were categorized into four main model categories (Discrete entity (particle) model, hybrid model, quantum-like model, and quantum model) and many other sub-categories. The analysis indicated that most student models in both groups fell into the discrete entity (particle) and hybrid model categories prior to instruction. Due to the abstract nature of quantum concepts, students had developed incomplete, incoherent, and inaccurate models even after being taught those concepts in chemistry or physics courses.

Based on similar findings in a pilot study conducted prior to this study, I developed a model-based learning module (MBLM), which consisted of six lessons and two to three model-based inquiry activities per lesson. The significance of the MBLM is not limited to providing visuals or physical manipulatives to help students visualize abstract concepts, but also provides a well-organized guide that encourages students to use models to express their reasoning and make connections between different types of models. Students who received MBLM illustrated more consistent and meaningful model refinement.

8.2 MBLM students' model refinement process

With the results of MBLM implementation, I also discussed the model change progress for each individual who received the model-based learning module. Since the

development of early atomic theories led to the discovery of the quantum mechanical atomic model, it is very important to understand the experiments and the reasoning behind all the evidence in a heuristic perspective (Matthews, 1994; Schwab, 1962, 1974). In the model-based inquiry activity related to the Thomson model, students were given a situation where they had a spherical ball and were required to predict and then observe what was inside the ball. In most cases, their prediction was based on the classical view where they employed a very deterministic prediction such as thinking the skewers either should go through or be stopped by some objects inside. After observation, students recognized the objects placed inside the ball and drew a model based on their observations. However, since the planetary model was dominantly rooted in the students' minds, they were prone to draw a large spherical object at the center of the ball even though there was nothing at the center of the ball. However, when the students were introduced to another model for Thomson's atomic theory, they were able to combine both models to conceptualize the intended idea. When they engaged with another hands-on model, which simulated a cathode ray tube experiment, they were able to comprehend how Thomson was able to discover electrons and their charge. Although two students referred to magnetization before they actually made the observation, all of them changed their models to the scientifically accurate model. Once they learned Thomson's model and the reasoning behind his theory, they were able to synthesize Rutherford's model via a physical model and a Rutherford scattering simulation. With the physical model, they confirmed their existing model of a large nucleus at the center of the ball, and with simulation, they realized how the size of the nucleus (number of protons) affects the trajectory of alpha particles. All students realized that a bigger nucleus means scattering

with wide angles of reflection. After the Rutherford model activities, they started thinking about what led early scientists to propose the planetary model of the atom. At this point, the discussions among students gave them opportunity to talk about how Thomson's model was not correct, what aspects of the atom the model did explain, and what aspects it could not. The same process occurred after they completed the Rutherford model and planetary model activities. Since the simulation for the planetary model did not providing anything besides a demonstration, students discussed why the electron was losing its energy and collapsing into nucleus after observing an electron's motion. In that sense, they referred to Maxwell's theory about accelerating objects.

The Bohr model activities helped students gain an intuitive understanding about Bohr's postulates and his mathematical model for calculating each energy level's distance to the nucleus (Bohr radius). The analysis of pre-questionnaire responses showed that students' knowledge about Bohr theory was limited to atomic representation. However, during the model-based inquiry activities, they had a chance to discuss and synthesize the postulates that led Bohr to assert his theory and derive the Bohr radius. Although not all MBLM students were able to recall all the postulates in the post-questionnaire, they gave reasonable explanations to support their responses. Nevertheless, the spectral line series still remained unclear for most students even though those were discussed several times during the lesson. The main reason for those to remain unclear may be because there was not a specific model used for these concepts in the MBLM. Unfortunately, it is very challenging to find a good model and develop an activity for every abstract concept. Therefore, some concepts were touched upon only via textbook reading or as part of discussions.

Over the entire course of the systemic model-based inquiry activities, students also revised and refined their models of electron behavior in an atom. They demonstrated more scientifically accurate models of arrangement of electrons in an atom based on Pauli and Aufbau principles and Hund's rule. They also altered their models of quantum numbers. Before the implementation, their models of quantum numbers were either in the discrete entity (particle) or hybrid model stage. Therefore, most of them tried to represent electron configurations based on memorization, which affected valence shell representation. After MBLM, they were able to define what each number and symbol meant and how they decided what comes after another shell or subshell. Orbital notation, on the other hand, was a very challenging concept for students. Initially, none of the students remembered or knew how to represent orbital notation. After they had completed it couple times as part of the MBLM activity, they executed a correct representation on their worksheet and inter-lesson assessment. However, when asked about it in the post-questionnaire, five of the students confused it with electron configuration. It appears that the differentiating between these two types of representations was not emphasized enough in the MBLM lessons and activities.

These activities built a good baseline for students to develop the quantum mechanical atom model. After learning electron arrangements and quantum numbers, students observed the de Broglie wave model and the Schrodinger model of the atom and explained the differences between the models using scientifically appropriate terminology such as electronic transitions, shell, subshell, and orbital. Before the MBLM activities, these terms were not completely understood by students. They tended to use more than one term interchangeably and inconsistently, but after they completed

activities, the terms became more clear and consistent. Moreover, through deriving the Schrodinger equation, students began to gain a steady understanding about the transition from the classical mechanical atom model to the quantum mechanical hydrogen atom. After all the systematic model-based inquires, students began to refine their model of atom. Only one student (Student M3) held on to her initial model of atom representation (Bohr-valence shell model) in her post-questionnaire responses. However, she was able to state electron configurations and s and p orbital representations in another question. The other two students successfully represented hydrogen and multi electron atoms by using orbital representation. Student M1 showed the probability density in his hydrogen atom representation even though he was not asked specifically about it.

Overall, MBLM seemed to facilitate the model alteration process in a more meaningful and scientifically accurate way. By using different models, students consolidated their conceptual understanding and developed sophisticated model-based reasoning for fundamental quantum mechanics concepts. However, there was also evidence that MBLM did not benefit all students the same. While five students shifted their models of energy levels and atomic spectra directly from discrete entity (particle) model to quantum-like or quantum models, three of them ended up at the same model stage or shifted to a hybrid model for atomic structure.

8.3 Which type of instruction is more effective for students?

Students' existing knowledge and models help them to make predictions about and explain phenomena and to understand new scientific knowledge (Chi, 1985; Glaser, 1984). In this study, I compared students' model development in two different learning environments: model-based learning module (MBLM) and traditional computer-based

simulation. Students in both groups reported having a similar background before the implementation and similar initial models about atomic structure, energy levels, and atomic spectra. After implementation, students' model evolution process and final models differed from each other based upon what stage that their initial models were in. The analysis showed that students in each type of instruction who initially had quantum-like models appeared to revise and refine their models to almost the same extent. The learning environments with computer simulations provided students with experiences observing simulated physical phenomena. Since expert-level students already had a virtual picture of abstract concepts and imagine some objects in 3D, they did not gain a lot after engaging with model-based activities. A significant number of student models that were initially at the hybrid model level shifted to the quantum model category with students demonstrating more accurate conceptual understanding after engaging with the model-based inquiry activities when compared to the traditional computer based simulations. This analysis demonstrates that model-based inquiry provides a better sense-making process and helps individuals who already have partial/mixed understanding about fundamental quantum concepts to connect concepts that are more complex. Since many high school and undergraduate students already have incomplete and hybrid models of many quantum concepts, the importance of this finding to facilitate students constructing meaningful understanding increases. In agreement with many studies, this study confirmed that students' prior knowledge or existing models are very important in predicting how students learn and how much they learn (Hrepic et al., 2007). As Stull et al. (2012) suggested, the model-based inquiry activities were more effective when novice

students whose models were in the discrete entity (particle) model level received some guidance before their engagement with the models.

After student engagement with the simulations, I realized that in some computer-based simulation engagement, TCBS students' observational notes deviated from the learning objectives of that particular lesson. If they are not sufficiently guided, they tend to focus on a different aspect of the simulated phenomena. Since not all the simulations were available for user interaction and manipulation, these simulations did not go beyond being a demonstration and were not much different from pictures in the textbooks. Some other simulations, on the other hand, turned out to be quite complicated without instructions. Another disadvantage of using only computer-based simulations was having very constrained interaction with users. Most simulations only show the outcome or some process of a physical phenomenon. The user's task is limited to changing some of the variables. Observing a direct result based on adjusting the configuration for themselves might help students who do not have enough background and are unable to run a deep thinking process. However, it does not provide any further understanding for students who are at a higher cognitive level or have higher conceptual understanding.

When MBLM students took advantage of using multiple types of models supported by guided instructions and discussions, their discrete entity (particle) and hybrid models benefited more than the TCBS students' discrete entity (particle) and /or hybrid models. Meaning, if students does not have enough background knowledge about the physical concepts, they can gain more accurate conceptual understanding and more consistent scientific reasoning by using different models. When different types of models are used in a learning process, learners have the chance to engage with task-relevant

manipulation and gain long-term learning (Stull & Hegarty, 2016). Therefore, this study confirmed the importance of knowing students' initial models before designing types of instructions and preparing learning tools.

Students' perceptions regarding the format of the instructions were identified via an exit questionnaire that all students were requested to fill out at the end of every lesson. The questionnaire inquired as to whether or not students understood the physical concepts delivered in that particular lesson and what they thought about the activities. Students' responses to the questionnaire varied based on the activities of the day. Below are some examples from students regarding what they thought about the format of the particular classes:

M1: I like how we start of by looking at various models that reconnect to bigger idea.

M2: Well organized with a lot of activities. Maybe a bit too much repetition?

M3: I like the engagement- I learned better & will probably remember more things covered today.

M4: It is helpful for more practical and visual learning compared to reading textbooks.

MBLM group students' overall comments were positive toward engaging with different activities and models. They thought most activities were helpful to them in understanding the concepts and making connections between different ideas. Moreover, in one of the comments that M3 made, she claimed that the activities were very engaging and that they will help her to remember things later.

While students' perceptions of taking advantage of the model-based inquiry activities were promising, sometimes they complained about the length and the number

of activities. Therefore, it is important to keep the activities concise yet comprehensive (see section 7.4).

T1: The reading and discussions are both good. The simulations are as well, but not as reinforcing

T2: It's okay. [I] wonder if there is a more time efficient way than reading by myself.

T3: I think the reading / worksheet / simulation pattern is a good format for learning

T4: The classroom environment was very helpful.

Although a small selection of the comments was presented, these are a strong representation of the rest. Half of the traditional group students thought that the format of the course was very helpful. They believed that reading and simulations were two important components for their understanding. However, one student consistently claimed that reading was not helpful at all. Even though the traditional group had little discussion about the physical contents, most students found that discussions were useful. Simulations, on the other hand, appeared to leave mixed impressions on students. For particular simulation activities such as planetary model, quantum hydrogen atom models, etc., students found them less effective compared to other learning materials.

8.4 Directions for future research

The ultimate purpose of this thesis study was to examine the effectiveness of model-based inquiry on the conceptual understanding of freshmen physics and engineering students. The overall results were in alignment with the initial assumptions about the effectiveness of MBLM that made by current literature. Students who engaged with different models appeared to refine and revise their models toward the targeted

model and alter their perceptions about the difficulty of fundamental quantum concepts. However, the results also indicated that some model-based inquiry activities such as atomic spectra and electron spin did not function as expected. The students did not appreciate the activities that took a long time to complete or those that did not have sufficient guidance. Therefore, future model-based inquiry activities must be carefully revised by maintaining the principle theme but reducing the amount of labor.

Conversely, the discussions related to every model used were agreed to play a significant role in comprehending the models in more detail and recognizing the connections between real phenomena and models as well as models themselves. Students mentioned that they learned a great deal when they discussed their observations and experiences involving the models with their partners. Hence, future studies should also consider encouraging learners to discuss their models more often and express their reasoning using models.

Due to the qualitative nature of this study, I worked with only 7 students in this research study (one dropped out in the middle of the study) and analyzed each student's model evolution process in detail. These analyses provided information in terms of how each individual received the physical, virtual, graphical, and mathematical models; how they processed the models mentally; and how they revised internal models based on their experience after each engagement. Moreover, the small data set also demonstrated that students' initial model stage might be a useful indicator of what type of instruction (MBLM or TCBS) would facilitate better performance in terms of model transitions. However, in order to make a strong claim, future studies should seek to examine model

transitions via engaging in MBLM or TCBS with a larger sample size. With more data, this assertion will be backed up by more tangible and generalizable findings.



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APPENDIX A. PRE-SCREENING SURVEY

PRE-SCREENING PARTICIPANT CONSENT FORM

Undergraduate Students' Understanding of Concepts Foundational to the
Learning of Quantum Mechanics (QM) via Modeling-Based Instruction Alejandra

J. Magana, Assistant Professor

Departments of Computer and Information Technology

Tugba Yuksel, Ph.D. Candidate

Department of Curriculum and Instruction, Purdue University

Purdue University

What is the purpose of this study?

The purpose of this study is to investigate what are students understanding of quantum mechanics related concepts (e.g., atomic structure, energy levels, atomic spectra) With having ideas about students' understanding, we can develop learning materials and simulation tools that can help students better understand these concepts.

What will I do if I choose to be in this study?

We are asking your participation as volunteers by first filling out the pre-screening survey. If you are selected, you will be asked to answer couple questions about quantum mechanics concepts at the beginning and at the end of the engagement of few quantum mechanics learning activities over a period of 8 non-consecutive days. We will observe and videotape during your engagement with learning activities. If you are willing to be videotaped, our camera will capture your work only; your face will not appear in the

video. By agreeing to be videotaped, you are simply allowing us to videotape the interviews and the work you do during 8 sessions

How long will I be in the study?

Your involvement in this project will last for 4 weeks after spring break. A total of 8 activity sessions and a total of 2 short interview sessions will be videotaped.

What are the possible risks or discomforts?

We believe that this study will present minimal risks to you. A breach of your confidentiality is a risk in this type of research because of the type of data we collect. The precautions we take to prevent a breach are described in the Confidentiality section below.

Are there any potential benefits?

There are no direct benefits to participants. You can take advantage of having extra quantum mechanics instruction. What we learn as a result of your participation does have the potential to improve physics instruction and, thus, to benefit future students.

Will I receive payment or other incentive?

There is no compensation for pre-screening survey. However, if you are selected, you will have an opportunity to get paid \$10 /hour to help us (1) by answering questions about some of the quantum mechanics concepts at the beginning and at the end of the implementation; and (2) by attending two days per week over a four-week period of implementation. Your participation is strictly voluntary. Since there are 10 total meet ups (including interview and learning activities), each lasting no more than an hour, your total compensation will be \$100

Amazon gift certificate to compensate you for your time if you complete the study. The payment will be granted within a few days upon completion of the study.

Will information about me and my participation be kept confidential?

The project's research records may be reviewed by departments at Purdue University responsible for regulatory and research oversight. All videotaped data and document collected during the study will be kept in a secure location at Purdue University West Lafayette campus accessible only to the principle investigator and key personnel. Videotapes and audio records will be transcribed within 6 months and destroyed within 3 years.

The names and identities of all participants will be protected by replacing their names with reference codes on all documents collected and in all transcripts. Those reference codes will be used to refer to participants in any publications or other documents prepared to report results of the study. Students' names will be removed from the transcribed data.

What are my rights if I take part in this study?

Your participation in this study is voluntary. You may choose not to participate or, if you agree to participate, you can withdraw your participation at any time without penalty or loss of benefits to which you are otherwise entitled.

Who can I contact if I have questions about the study?

If you have questions, comments or concerns about this research project, you can talk to one of the researchers. Please contact Dr. Alejandra Magana at admagana@purdue.edu / (765)494-3994 or Tugba Yuksel at tyuksel@purdue.edu

If you have questions about your rights while taking part in the study or have concerns about the treatment of research participants, please call the Human Research Protection Program at (765) 494-5942, email (irb@purdue.edu) or write to:

Human Research Protection Program - Purdue University

Ernest C. Young Hall, Room 1032

155 S. Grant St., West Lafayette, IN 47907-2114

Documentation of Informed Consent

I have had the opportunity to read this consent form and have the research study explained. I have had the opportunity to ask questions about the research study, and my questions have been answered.

Please click "yes" if you wish to proceed. If you do not want to proceed please click "No" to exit the survey

- ☐ Yes, I am prepared to participate in the research study described above.
- ☐ No, I am not prepared to participate in the research study described above.

Q1. Please write your full Name

Q2. Please enter an email address that we can reach you

Q3. What major will confer the degree you are seeking?

- ☐ Physics
- ☐ Chemistry
- ☐ Biomedical Engineering
- ☐ Electrical Engineering
- ☐ Materials Engineering
- ☐ Other (Please specify

Q4. What is your year in college?

- ☐ Freshman
- ☐ Sophomore
- ☐ Junior
- ☐ Senior
- ☐ Graduate Student

Q5. Have you ever taken any modern physics/ quantum mechanics course since you started seeking undergraduate degree?

- ☐ No
- ☐ Yes (Please write the course name or if more than one course separates them by comma)

Q6. Have you ever seen atomic structure and atomic spectrum concepts as part of? physics or chemistry curriculum in high school?

- ☐ No
- ☐ Yes (please briefly describe under which subject and in what extent)

Q7. Please answer this question, if your answer "Yes" to Q5 and Q6. Otherwise, go to Q8.

In which ways have you learned quantum mechanics related concepts in high school or College? (e.g., course, outreach, workshops, self-taught)

Please specify below

Q8. How would you rate the level of your knowledge and understanding in the following quantum mechanics concepts?

0 10 20 30 40 50 60 70 80 90 100

Atomic Structure

Energy Level /
Quantization

Atomic Spectra

Q9. How difficult it is to learn quantum mechanics based on your experience?

- ☐ It seems too difficult to understand
- ☐ It seems difficult, but it is not impossible to learn for me
- ☐ I do not have any idea how difficult or easy to learn
- ☐ It is quite straight forward to understand
- ☐ Other (please specify)

Q10. Please rank the best way you learn in science related courses?

- ☐ Listening Instructor carefully
- ☐ Reading textbook
- ☐ Doing experiments in lab
- ☐ Doing hands-on activities
- ☐ Other (Please specify)

Thank you for your interest in this project and for taking the time to answer these questions. We will contact you after an initial screening process.

If selected, the next step in the study consists of participating in two recorded interview (one will be before and one will be after engaging quantum mechanics learning activities), which might last up to 50 minutes and then engaging quantum mechanics learning activities over a period of 8 non-consecutive days. If you are selected to participate the study, we would like to schedule a meeting at a convenient time for you. Your responses will be confidential and your participation will not affect your grades or academic standing in any of your classes.

Please understand that filling out this survey does not mean that you will be automatically selected to participate in the recorded interview and implementation. Also, please consider that you will receive the Amazon gift certificate of \$100 few days after you have completed the study. Please note that you will not get paid if you prefer to leave study before completing the described implementation.

We will follow up with you soon

If you have any further questions you may contact Tugba Yuksel at tyuksel@purdue.edu. You may also contact Dr. Alejandra Magana at admagana@purdue.edu / (765)494-3994.

We appreciate your participation!

APPENDIX B. PRE-QUESTIONNAIRE

1) a) Please describe below everything you know about the Hydrogen atom.



b) Draw a hydrogen atom and label all parts



2) a) What can you tell about electrons in an atom



b) Can you represent that with drawing?



3) a) What does quantization of energy mean?



b) How is energy quantized in a hydrogen atom?

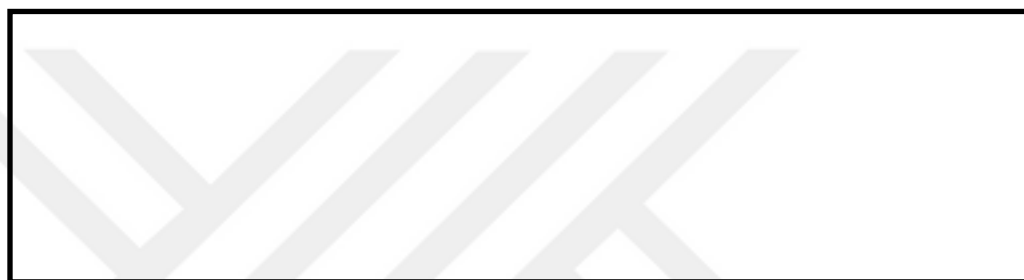


4) What happens if an electron jumps down from one energy state to a lower energy state?

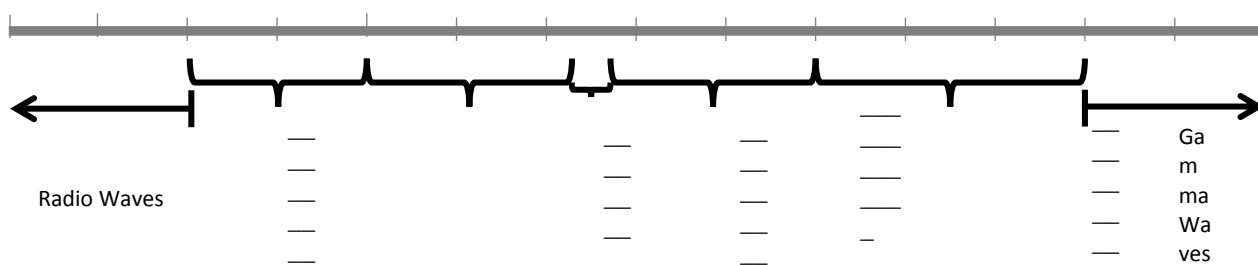




- 5) a) In a rainbow, which color has shortest wavelength and which color has longest wavelength? And why?



- b) A graphical representation of the electromagnetic spectrum is shown in the figure below. Please indicate the type of electromagnetic radiations (such as infrared, x-rays, visible light, microwave, and ultra-violet) between Radio waves and Gamma Waves.



The Electromagnetic Spectrum

- c) Which part of the electromagnetic spectrum has long wavelength, low frequency? Please mark your answer on the graph.

6) In 1802 William Wollaston noted that the appearance of dark lines in the spectrum of sunlight. These lines are due to the presence of certain chemical elements in gases surrounding the sun.*

a) Explain why sharp dark lines appear only at specific wavelengths.

b) Explain how a comparison between the spectrum of sunlight with the dark lines and the spectrum of light from a sodium lamp can identify that sodium is one of the elements in the Sun's atmosphere?

c) Which of the following statements is (are) true? (Circle below all that apply)

- I. An excited atom can return to its ground state by absorbing electromagnetic radiation.
- II. After an atom becomes excited, the electron remains in the excited state indefinitely.
- III. The energy of an atom is increased when electromagnetic radiation is emitted from it.
- IV. The energy of electromagnetic radiation increases as its frequency increases.
- V. An electron in the $n = 4$ state in the hydrogen atom can go to the $n = 2$ state by emitting electromagnetic radiation at the appropriate frequency.
- VI. The frequency and wavelength of electromagnetic radiation are inversely proportional to each other.

*This question is retrieved on January 2016 from :

https://www.nobraintoosmall.co.nz/students/physics/NCEA_Level3/L3_exam_help/collated_questions/pdfs/Atoms__Spectra.pdf

7) Match the definitions or principle to the related statement:

A. Lyman series	___ describes the orientation in space of a particular orbital
B. Principle quantum number	___ describes the direction of the electron's angular momentum.
C. Paschen series	___ describe emission lines of the hydrogen atom as an electron goes from $n \geq 2$ to $n = 1$
D. Orbital magnetic quantum number	___ an orbital can only hold a maximum of two electrons
E. Spin quantum number	___ describes the size of the orbital
F. The Pauli exclusion principle	___ describes emission lines from $n=3$ to higher energy levels
	___ describes the orientation in space of a particular orbital

8) a) Write the electron configuration for Fluorine, which has 9 electron and Krypton, which has 36 electrons.

b) Write orbital notations for the following atoms:

O (#e = 8) :

Co (#e= 27):

9) Please describe and draw an atom with multiple electrons

Description:

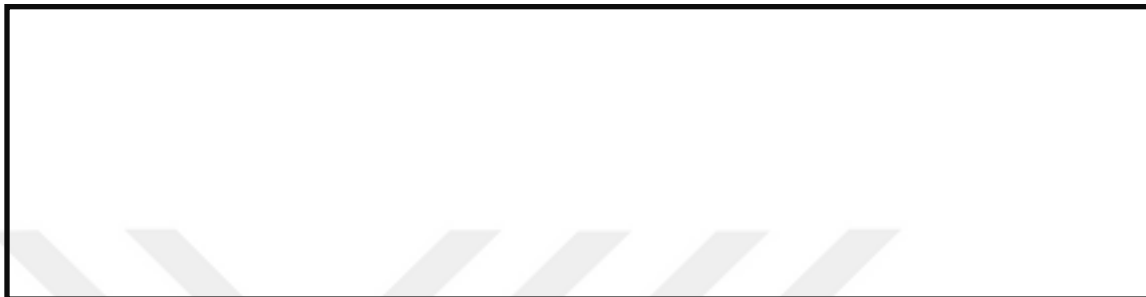


10) What can you tell about Quantum mechanical hydrogen atom? What do you know about, probability density, wave function, Schrödinger model?



APPENDIX C. MBLM STUDENTS' WORKSHEET**Pre-Unit Activity:**

1. What is model?



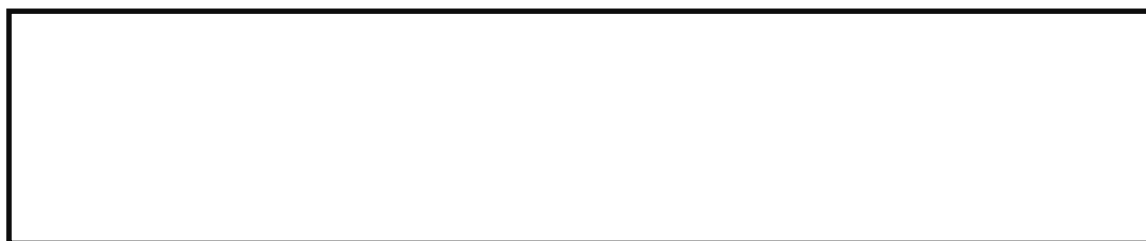
2. Why we use models in science?



3. What are advantages of using models? Please give example(s)



4. What are limitations of using models? Please give example(s)



UNIT 1: THE STRUCTURE OF ATOM

Lesson 1: History of Atomic Theory

Introduction:

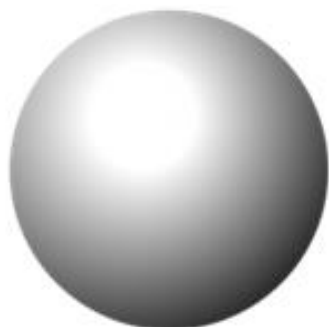
Questions

1. What is an atom?
2. How has the understanding of atom been changed from 17th century till now?
3. How do scientific theories evolve over time with each model?

PS. At the beginning of 19th century, there was not enough equipment that helps to examine and determine sub-atomic particles. However, scientists had to come up with some sort of experimental settings to find out what it is inside an atom and what its components are. Therefore, the earlier scientists developed some creative experimental designs, which allowed them to make observations and inference based on these observations. In this unit, we encourage you to think how scientists approached to problems, how they determined what they needed to do in order to find out the components of the atom, and how they used their reasoning to describe how an atom look like.

Activities:

Activity 1: What is it inside the foam ball?



- 1- Take one foam ball and 3 skewers. Note that the foam ball is sealed and it is impossible to see inside.
- 2- Discuss with your pair about how we can find out what there is inside the ball.

- 3- How would you expect that those skewers would go after you stick them through the ball?



- 4- Use the skewers to find out what it is inside the ball.
5- Record your observations (you may also draw what you think there is inside the ball).



❖ *Readings: Before starting the next activity, you can read Early Models of the Atom and Thomson Model on page 1*

Activity 2: How do electrons behave under the influence of electric field?

1. Take one incline ramp setup and a dozen small balls. For this activity, the small balls are representing electrons. For the purpose of the activity, you assume that the balls are not magnetized and you try to find out how those electrons are moving when they are influence of electric field.

2. What would you expect the small balls continue their motion after they leave the ramp? Please write your predictions with detailed explanation



3. Now, you will roll one ball at a time from the top of the incline ramp and observe what happens. You can discuss your observations with your pair
4. Please record your observations by giving details as much as possible. (you can draw pictures to support your explanations)

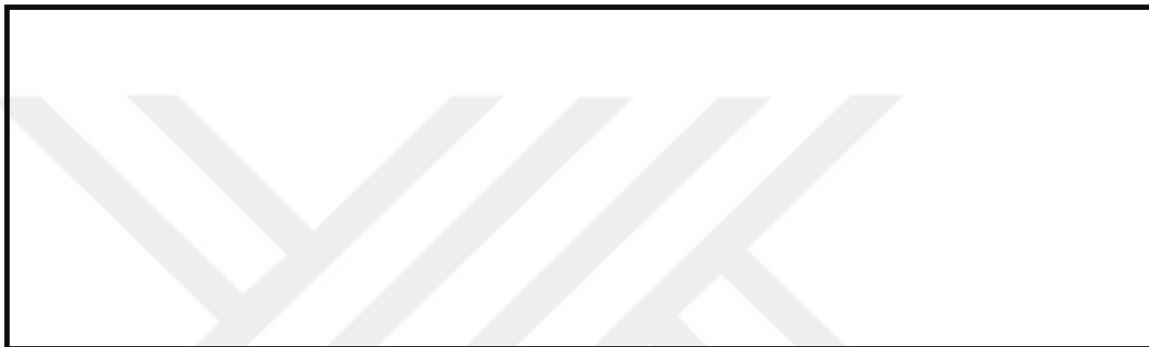


5. How would you connect this activity to electrons motion when they pass thru between cathode and anode plates? Why electrons behave like how they behave?

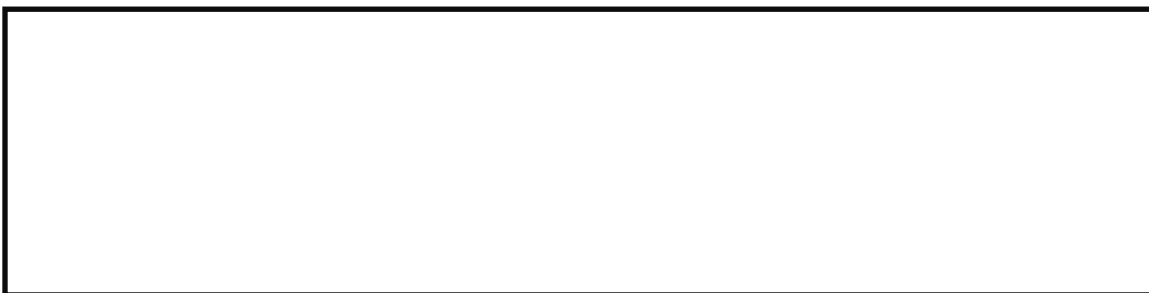


Activity 3: Plum Pudding Atom

- 1- Open the simulation by clicking the following link:
<https://phet.colorado.edu/en/simulation/rutherford-scattering>
- 2- Download and open the simulation.
- 3- Start with “Plum Pudding Atom” tab
- 4- Describe how alpha particles move after hitting the atom. What happens when you change the energy of alpha particles? Is there any difference?



- 5- Take notes what you observe on alpha particles' trace when they increase the energy.



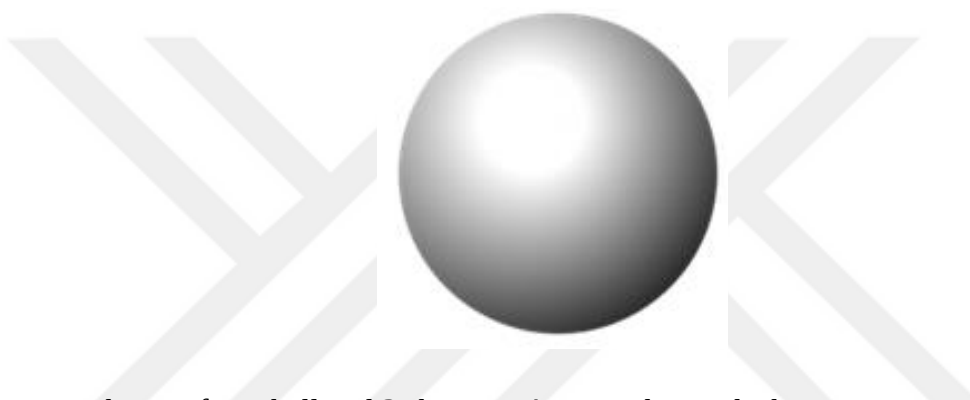
Discussion Question (in pairs): What are the similarities that you see between Activity 1 and Activity 3? What does Activity 1 tell us?

BB Discussion:

1. What does Thomson atom model explain and what does not?
2. What can you tell about Thomson atom model?

Activity 4: Let's test Plum Pudding model

We know how J. J. Thomson described an atom and its components. As a part of his absorption of radioactivity studies, Rutherford and his colleagues conducted another experiment with the assumption of the Thomson model which says *electrons were located as chunks distributed through a positively charged sphere* in their mind. Now, we will try to test if Thomson model of atom is a good representation of an atom or not by using a model similar to Rutherford experiment.



- 1- Take one foam ball and 3 skewers. Assume that each skewer represents a positively charged particle.
- 2- Hold the ball and start sticking the skewer once upon a time to the different locations on the ball.
- 3- How would you expect that those skewers would go after you stick them through the ball?

- 4- Based on your observations, draw what would be inside the ball

- 5- Explain what was your observations and how did you come to that conclusion. Please write down your reasoning.

❖ *Readings: Before starting the next activity, read Rutherford Model on page 1&2*

Activity 5: Rutherford Atom

- 1- Open the simulation by clicking the following link:
<https://phet.colorado.edu/en/simulation/rutherford-scattering>
- 2- Click on “Rutherford Atom” tab
- 3- Answer following questions:
 1. What happens when alpha particles are sent to the atom that has 20 proton and neutron?
 2. What happens when you increase the number of proton but keep the number of neutron the same?
 3. What happens when you keep the number of proton the same and increase the number of neutron?
 4. What happens when you increase the number of both proton and neutron?
 5. How energy of alpha particles affects its trace after leaving the gun?
- 4- Record your observations for each different trial on previous step.

- 1.
- 2.
- 3.
- 4.
- 5.

Discussion Questions:

1. What does Rutherford model explain and what does not?
2. What can you tell about Rutherford atom model?
3. (Submit as HW assignment) Why we use these models/ Analogies?
4. (Submit as HW assignment) What do you think about the models that we used during the lessons? In what way do you think that they were not representing the real phenomena?



Activity 6: Do electrons circle around nucleus?

❖ *Readings: Please read The Planetary Model on page 2-4*

1. Open the simulation by clicking the following link:
<https://phet.colorado.edu/en/simulation/hydrogen-atom>
2. Click on “Classical Solar System” tab
3. Explain the motion of electron according to planetary model.



4.

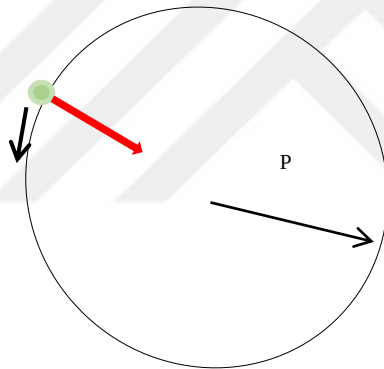


Figure 43 Diagram for Planetary model

The given free body diagram for planetary model of atom is given above.

Calculate the circular motion of an electron by using attractive force and electric force formula.

Here some useful values:

$$k = 8.99 \times 10^9 \text{ N} \cdot \text{m}^2 / \text{C}^2$$

$$e = 1.60 \times 10^{-19} \text{ C}$$

$$m = 9.11 \times 10^{-31} \text{ kg}$$

$$r = 1.0 \times 10^{-10} \text{ m}$$

Write your calculations here:



BB Discussion:

1. Why planetary model seemed to be a good representation of atom to Rutherford and his colleagues?
2. Why do you think this model was not accepted by fellow scientists like Niels Bohr?
 3. What do you know about Maxwell's theory of electromagnetic waves?



UNIT 2: ATOMIC SPECTRA

Lesson 1: Energy Quantization

Introduction:

Background requirement: Blackbody radiation, electromagnetic spectrum, Planck constant and the relationship between the speed of light, wavelength and frequency.

Questions:

1. What does quantization mean?
2. What is photon?
3. How can we calculate the energy of a photon?
4. What do ground and excited states mean?

❖ *Readings: Before coming to face-to-face meeting, please read Photons on page 5&6.*

Activities:

Activity 1: Hydrogen spectroscopy

1. Open the simulation by clicking the following link:
<http://phys.educ.ksu.edu/vqm/free/h2spec.html>
2. Create energy levels (including ground state & 5 excited states) and show transitions between those energy levels. Please make sure spectral lines on simulation screen exactly match to spectrum on real screen. Draw these energy levels with transition here.



3. Calculate the energy transition based on your energy level graph.

E_1
 E_2
 E_3
 E_4
 E_5

4. Now, click on “Simulation” button on top of the simulation screen, and then click “emission” link under “Spectroscopy Lab Suite”. Observe emission spectrum lines for each gas lamp by dragging the tubes to gas lamp socket. What can you say about those spectral lines?

❖ *Readings: Please read Electronic energy levels, Electronic energy levels of a hydrogen atom until collisional Excitation on page 5-8.*

BB Discussion:

1. How do spectrum lines occur?
2. What is the relation between spectral lines and energy levels?
3. What happens if energy levels were different? Or distance between transition lines was different?
4. What is the crucial information that indicates each atom has quantized energy levels and they show differences for each element's atoms?

Activity 2: Energy levels and Photon absorption of Hydrogen atom

1. Open the simulation by clicking the following link:
http://astro.unl.edu/naap/hydrogen/animations/hydrogen_atom.html
2. Please make observations of absorption of a photon that is sent with different energy (frequency / wavelength). You will try to find out what is the minimum energy (frequency / wavelength) for a hydrogen electron to jump to the first excited state, second excited state and so on.

Min energy to jump 1st excited state:

Min energy to jump 2nd excited state:

Min energy to jump 3rd excited state:

Min energy to jump 4th excited state:

Min energy to jump 5th excited state:

3. Calculate energy levels by using $E = (13.6 \text{ eV}) \left[\frac{1}{n_f^2} - \frac{1}{n_i^2} \right]$ and compare the results with your answer on your previous step.

$E_1 =$

$E_2 =$

$E_3 =$

$E_4 =$

$E_5 =$

4. Compare your results found in the previous steps with frequency / wavelength of $L_{\alpha}, L_{\beta}, L_{\gamma}, L_{\delta}$ and L_{ϵ} .

5. Now repeat the observation with a wavelength in visible range of the spectrum. What do you observe? And why?

6. Now, you will observe Lyman, Balmer and Paschen Series by sending photon to the electron and record the first energy differences for each series. Then you calculate those for hydrogen atom and compare the results of your calculations with energy difference that you recorded based on your observations. Here is

Hint 1: the Rydberg formula for your calculations: $\frac{1}{\lambda} = R(\frac{1}{n_1^2} - \frac{1}{n_2^2})$

Hint 2: Energy is inversely proportional to wavelength from the equation

$$E = h\nu = \frac{hc}{\lambda}$$

And Planck Constant (h) = $6.62607004 \times 10^{-34}$ m² kg / s

Lyman Series: The series of lines in the hydrogen spectrum associated with transitions to or from the first energy level or ground state.

Balmer Series: A series of emission or absorption lines in the visible part of the hydrogen spectrum that is due to transitions between the second (or first excited) state and higher energy states of the hydrogen atom.

Paschen series: The series of lines in the hydrogen spectrum associated with transitions to or from the third energy level.

❖ *Readings: Please read pages between 8-12, starting from Collisional Excitation.*

BB Discussion:

1. Why does electron not move until a photon with 10.2 eV is sent?
2. What happens when energy of photon that sent to electron is gradually increased?
3. What happens to the electron after it jumps to any excited states?
4. Why is it important to know about the Balmer series in atomic spectra for us? What is H_{α} ?

Lesson 2: Atomic Line Spectra & Energy Levels

Introduction:

Sunlight (white light) is a combination of all the rainbow colors, which covers all wavelengths of light. On the other hand, atoms in the form of gas, liquids, and solids can only glow at the specific wavelength (Hartmann, 1997).

Questions:

1. What are the examples of emission photons in our daily life?
2. What do you predict to see when you look at different spectrum of different gasses, such as helium, oxygen, hydrogen, mercury, neon?
3. How does atomic spectrum help to determine an unknown gas?

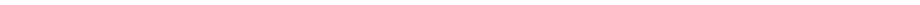
Astronomers use atomic spectra to identify the composition of gaseous clouds in outer space and stars (Simon and Smith, 2013). Each gas has unique signature group of lines that caused by electron transitions from one energy level to another. Therefore, an atomic spectrum is like a fingerprint for each element.

Activities:

Activity 1: Gas discharge Lamps

1. You will study the spectrum of gas discharge lamps and record the number and sequence of colors observed.
2. Take different gas discharge lamps and identify the gas inside the tubes by recording bandwidths of each color observed in nm. You may need to iterate the process to have accurate results.
3. First, write down your prediction of gases on the table below. And then mark the spectral lines on the scale that is provided below.
4. Calculate the energy in eV for each line recorded and determine each element by using those elements' actual spectra lines.

Unknown Gas No. 2:



350 400 450 500 550 600 650 700 750

Wavelength (nm)

[illegible]

Reference Line Spectra at Visible Wavelengths (nm):

[illegible]

Argon	Helium	Hydrogen	Nitrogen	Oxygen	Neon
416	447	410	410	395	470
420	469	434	485	437	540
427	502	486	492	533	576
697	588	656	496	544	585
707	668		528	596	620
727	707		576	616	640
738			648	645	693
750			746	700	724

BB Discussion:

1. What type of spectrum is observed in the first step? Was that emission or absorption?
2. How does the emission and absorption spectrums give different results?
3. Explain how were you able to determine the type of the gases?

Activity 2: Simulation: Atomic Absorption and Emission

In this activity, you will be able to observe the collision of photon and atom(s) in sub-atomic level.

1. Open the simulation by copying & pasting the following link:
http://www.cengage.com/chemistry/book_content/0495012017_skoog/student_website/as_ie2.html
2. Click “Atomic spectra” link, which is located under “An Introduction to Optical Atomic Spectroscopy” section.
3. You will make at least 5 trials and record what happens to the hydrogen atom when a photon with different wavelength is sent. You also will try this experiment with all three different wavelengths. Please do not forget to record the wavelength that you make your observations.

Wavelength	
1. Trial	
2. Trial	
3. Trial	
4. Trial	
5. Trial	

Wavelength	
1. Trial	
2. Trial	
3. Trial	
4. Trial	
5. Trial	

Wavelength	
1. Trial	
2. Trial	
3. Trial	
4. Trial	
5. Trial	

4. Explain the emission after collision by using energy levels diagram (on the right side of the screen)



5. What did you find out about hydrogen atom after observing all the trials with different wavelengths? Please discuss your observations with your pair and write a brief summary.



6. Once you finish all the trials with all three wavelengths, continue to answer the questions given on the simulation.

❖ *Readings: Please read Atomic Spectra Chapter on pages 13-21.*

BB Discussion:

1. What happens when a photon collides with an atom?
2. When you repeat the experiment, do you observe the same type of emission each time? Why or why not?

UNIT 3: BOHR'S MODEL OF THE ATOM

Lesson 1: Bohr Model

Introduction:

Questions:

1. What are the assumptions that Bohr model of atom made?
2. What is Bohr orbit and how can Bohr radius be calculated?
3. Why is there similarity between the wavelengths in the spectrum of light emitted by excited He^+ ions and the wavelengths emitted by excited H?
4. What are the similarities and differences between planetary model and the Bohr model?

Activities:

Activity 1: The Bohr Atom Model

1. Open the simulation by clicking the following link:
http://highered.mheducation.com/olcweb/cgi/pluginpop.cgi?it=swf::800::600::/sites/dl/free/0072482621/59229/Bohr_Nav.swf::The%20Bohr%20Atom
2. You will play with radius of the atom model and observe how emission lines are located.
3. By using the hydrogen emission spectrum table, you will rearrange the Bohr radius of the atom (try to get as close as possible result). Here, you will try to find correct first four radii for the hydrogen atom by matching the wavelengths.
4. You should also be able to find the right radius by using Bohr radii formula.

Hints: You can use,

$$h = \text{Planck's constant} = 6.627 \times 10^{-34} \text{ Js}$$

$$F_e = \frac{kq_1q_2}{r^2} = \frac{ke(-e)}{r^2} \quad (1)$$

$$F = m \frac{v^2}{r} \Rightarrow \frac{ke(-e)}{r^2} = m \frac{v^2}{r} \Rightarrow \frac{ke^2}{r} = mv^2 \quad (2)$$

$$L = r p \quad (3) \quad p = mv \quad (4)$$

$$L = r m v \sin \theta \quad (5)$$

$$L = r m v = (6)$$

$$\text{The condition for } n\text{th allowed orbits will be } L_n = r_n m v_n = \frac{nh}{2\pi} \quad n=1,2,3,\dots \quad (7)$$

$$k = 9 \times 10^9 \quad e = 1.6 \times 10^{-19} \text{ C} \quad m_e = 9.11 \times 10^{-31} \text{ kg}$$

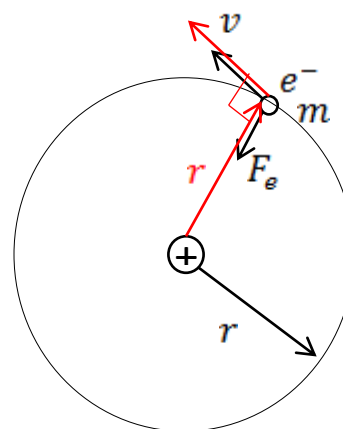
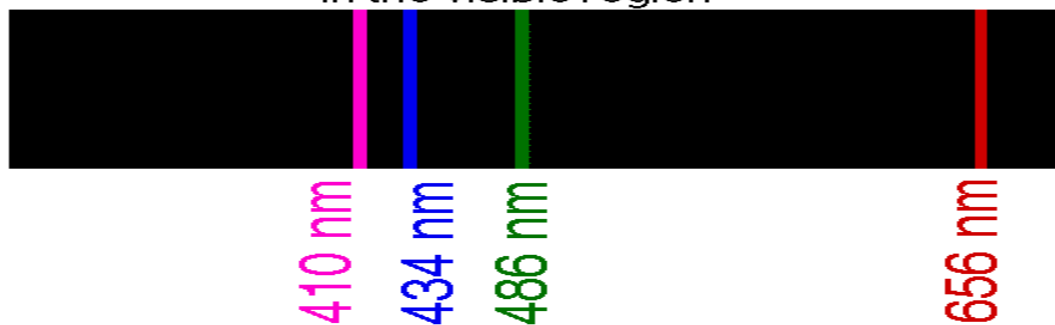


Figure 44 Bohr

Write your calculations here:



Hydrogen emission spectrum
in the visible region



Activity 2: Energy of an Electron

The orbit energy E is the sum of the potential energy, T , and kinetic energy, V , of the electron moving around the nucleus. So that

$$E = T + V = \frac{1}{2}mv^2 - k\frac{e^2}{r}$$

Here, kinetic energy component has v component versus potential energy has r component. That means electron's internal energy in a specific energy level determined by its kinetic energy, because in the same energy level, all electrons have the same potential energy. If an electron goes up or down between energy levels, its potential energy changes.

$n = \infty$	-----	$E = 0$
$n = 4$	=====	$E = -0.85 \text{ eV}$
$n = 3$	=====	$E = -1.51 \text{ eV}$
$n = 2$	-----	$E = -3.40 \text{ eV}$

$n = 1$ ----- $E = -13.6 \text{ eV}$

1. Based on the energy levels of hydrogen atom diagram, what would you say about the energy of an electron when it goes away from the nucleus?

PS: This energy is negative because it is energy which must be supplied to get the electron away from the electrostatic attraction of the nucleus.

2. You will now study electron potential energy change by its distance to the nucleus. What do you think if the electron jumps up to higher energy levels, what happens to its potential energy? Increase or decrease? And why?

3. Take the energy level model and one sphere shape magnet. Stating from $n=1$ to higher energy levels try to observe the magnitude of magnetic attraction between the ball and the magnetic platform. How would you rank the magnitudes? And why do you think the magnitude of magnetic force change or remain the same in different levels?

4. What can you say about the energy released by an electron when it jumps down to lower energy levels? What kind of energy does an electron lose?

❖ *Readings: Please read Bohr Atom Model Chapter on pages 22-28.*

BB Discussion:

1. How does Bohr model approach to stability of atoms and to atomic spectra?
2. Why is there a similarity between the spectrum of light emitted by excited H atom and the wavelengths emitted by excited He^+ ? Explain...
3. Why Bohr model was not accepted as currently scientifically accepted atomic model?

UNIT 4: WAVE MECHANICS AND THE HYDROGEN ATOM (QM HYDROGEN ATOM)

Lesson 1: Quantum Numbers

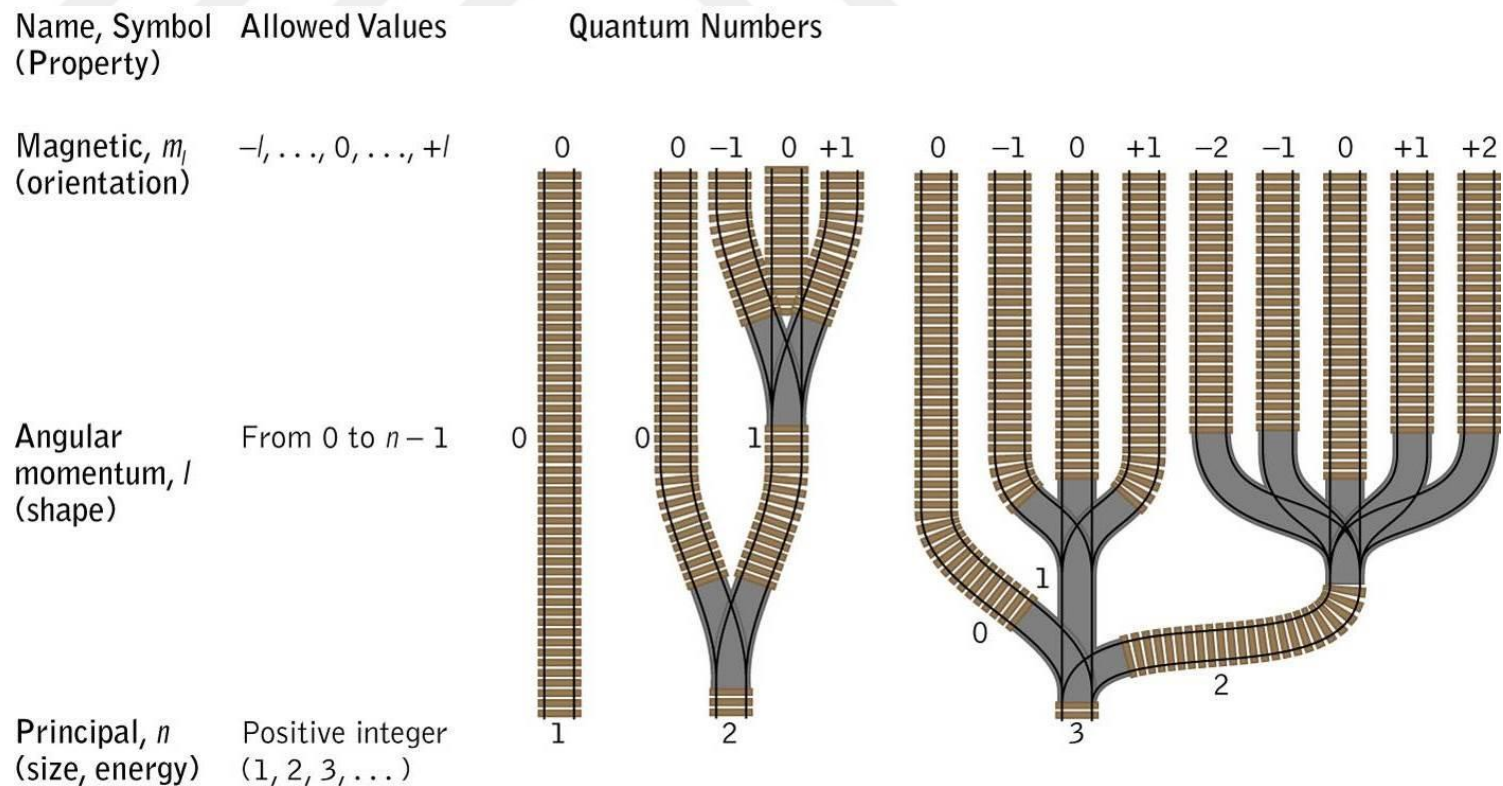
Introduction:

Bohr atom model explains some phenomena for hydrogen atom (such as atomic spectra) but it is lacking in helping to understand multi-electron atoms (Sharma, 2008). However, upon emergence of quantum mechanics, scientists were able to explain those phenomena with more meaningful understanding.

In 1924, Louis de Broglie (1892 – 1987) started asking questions like *if light could behave as a wave and a particle, could matter (which we think of as particles) behave as a wave based on the idea of nature likes symmetry* (Deb, 2013). Erwin Schrodinger (1887-1961) asserted a wave equation to describe electron matter waves, which was propounded by de Broglie. This equation states how a wave associated with an electron can take different positions in space. Schrödinger wave equation worked to explain the hydrogen atom as well as it did for multi-electron atoms.

Quantum Number	New students
Principle Quantum Number (n)	Determines the position or energy level that electrons are moving. Only integer numbers $n=1, 2, 3, \dots$
Orbital Quantum Number (l)	Determines the shape of the path in which the electrons are moving (s, p, d and f)
Magnetic Quantum Number (m)	Determines the orientation in space of the p-shaped orbits along the x, y, and z-axes.
Spin Quantum Number (s)	Determines that within each pair of electrons, one electron spin clockwise and the other spins counter-clockwise.

Quantum Number Relationships



Activities:

Activity 1: Finding Quantum numbers of electrons

You will use

$$n = 1, 2, 3, \dots$$

$$l = n - 1$$

$$m = -l, -l + 1, \dots, 0, \dots, l - 1, l$$

$$s = -\frac{1}{2}, \frac{1}{2}$$

And calculate:

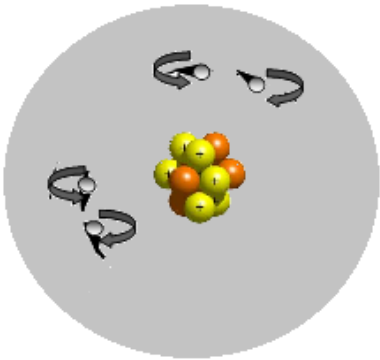


Figure 45 Electron

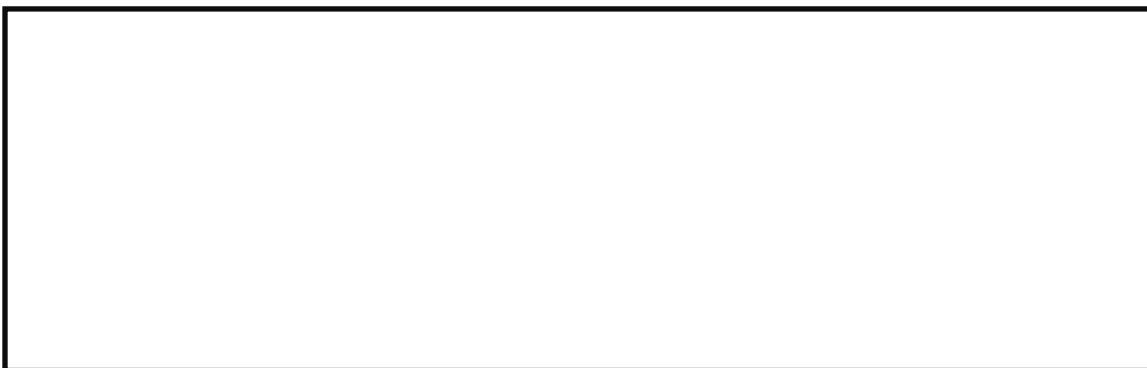
The 4 th energy level has 4 sublevels called:	- 4f, has 7 orbitals called 4f and can have 14e - - -
The 3 rd energy level has 3 sublevels called:	- - -
The 2 nd energy level has 2 sublevels called:	- -
The 1 st energy level has 1 sublevel called:	-

Activity 2: Quantum Models of Hydrogen Simulation (de Broglie and Schrodinger models)

1. Open the simulation by downloading it from the following link:
<https://phet.colorado.edu/en/simulation/hydrogen-atom>
2. Click on “de Broglie” tab
3. You will start with de Broglie model. Clicking on experiment, you will first observe what happens when white light is shot at the hydrogen atom.
4. Then, you will turn on the “prediction” and make couple more observation by changing the light to monochromatic light, and record the changes on energy levels and absorption/emission spectroscopy. You can also look at the atomic view from 3D option.



5. After you finish making observation on de Broglie wave model, repeat the same process with Schrodinger atom model. As an extra step, you will excite the atom and record how quantum numbers change and how these changes are reflecting on energy levels diagram.



6. Find the relationship between frequency and wavelength

7. Find the frequency of green light with a wavelength of 512Å.

❖ *Readings: Please read Wave Mechanics and the Hydrogen atom on pages between 29-32.*

Activity 3: Schrodinger Equation

1. Now, you will derive Time Independent Schrödinger equation with the help of basic knowledge of algebra and calculus and some general physics.

Equations you need to remember:

$$T = \frac{1}{2}mv^2$$

$$p = mv = h/\lambda$$

$$E = hv = \hbar\omega$$

$$K = \frac{p^2}{2m} \quad \text{or} \quad k = \frac{2\pi}{\lambda}$$

And wave function: $\psi(x) = Ae^{i(kx - \omega t)}$

To do this derivation keep in mind that energy conservation, which is classically used to represent the total energy E of a particle in terms of the sum of its kinetic energy T, and its potential energy V.

$$E = KE + PE$$

2. Think about one-dimensional motion and start taking derivative of wave function to find momentum component of the energy conservation equation. As later step, you will plug the value of momentum into kinetic energy equation. PS. You will multiply the whole equation with wave function (Ψ).

Hint: This wave function corresponds intuitively to our classical notion of a particle bouncing back and forth between the walls of the potential well. The appropriate wave function for a free particle of momentum $p = \hbar k$ and energy $E = \hbar\omega$.

Write your calculation here



BB Discussions:

1. How De Broglie, Schrodinger and Heisenberg did develop their theories over time that constructed the essential themes for today's understanding of the atomic structure?
2. What is your understanding on the nature of electron? Is it wave or particle? Explain your answer.
3. Why it is important to know quantum numbers?

Lesson 2: Multi-Electron Atoms

Introduction:

So far, we looked at atoms with a single electron. Now, we are going to examine the atoms with more than one electron. Hydrogen atom has quite simple structure and its electron's configuration is relatively easy to understand. However, multi-electron atoms have more complicated structure. Moreover, the simple energy expression that we used for hydrogen atom cannot be used for multi-electron atoms. Here, quantum numbers will help us to identify the electron configuration for the atoms have more than one electron.

Activities:

Activity 1: Pauli Exclusion Principle

For this activity, we will show how electrons are arranged in different energy levels based on Pauli Principle.

Materials:

7 glass vials

27 small marbles (different colors) Marbles should be as small as the size that 3 marbles can fit in one vial's base.

1. Students will be asked to fill the vials one marble at a time. They will go to the second marble starting from second vial. And so on.
2. Ones the first layer of marble took the entire place on the third vial's base, they will start filing the second layer on the fourth vial. The last vial will have the third layer.

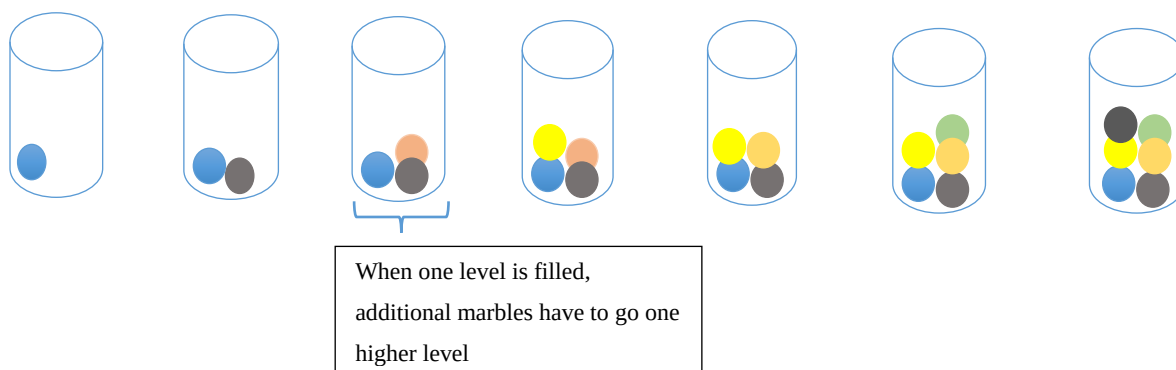
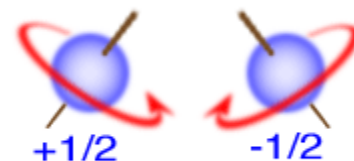


Figure 46 Model view for Activity 1 of Lesson 2

3. What is your conclusion about this model? How would you explain Pauli Exclusion Principle based on this model?

Activity 2: Electron Spin

1. You will take one of each electron spin up and spin down models. Now you will try to demonstrate Pauli's exclusion principle that if there are two electrons in the orbital, they must have opposite (paired) spins. This means if one is assigned an up-spin ($+1/2$), the other must be down-spin ($-1/2$).



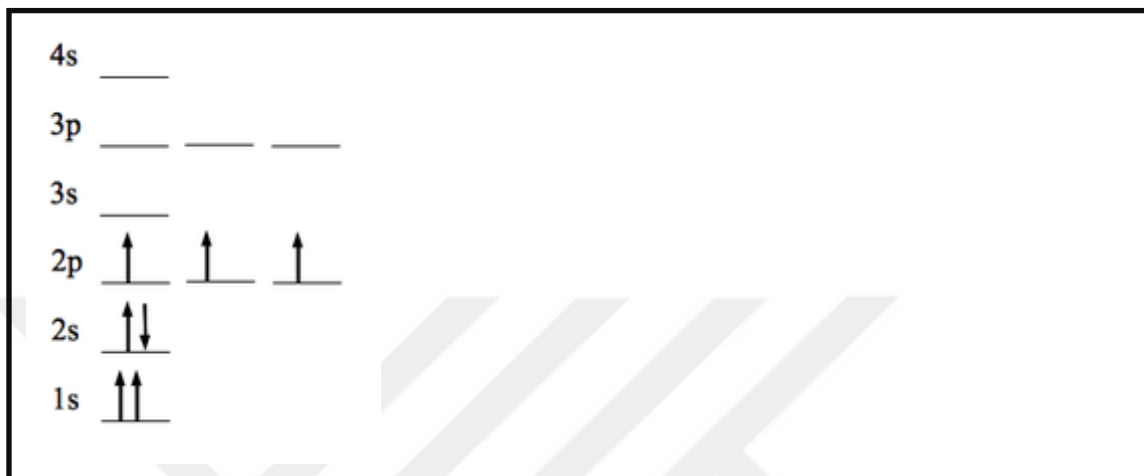
2. Let's say there are two electrons with spin up. If one of these electrons were added to an alpha particle (He^{2+}) we would have a He^+ ion with an electron with a spin up. If we were to add the second electron to this ion what would happen?

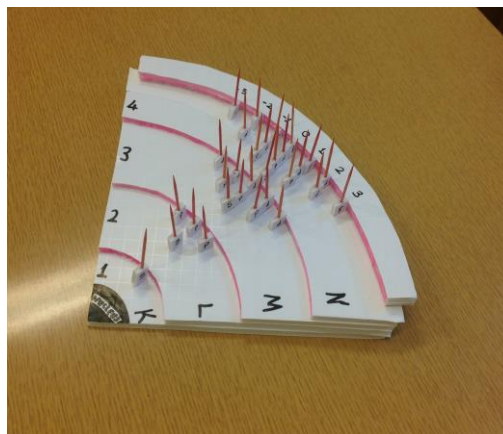
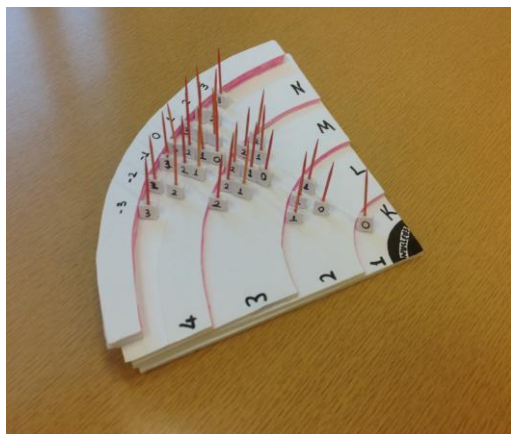
Activity 3: Electron Configuration and Aufbau Principle

1. Based on Aufbau principle, an electron always occupies the lowest energy orbital first before filling the higher level. For example, an electron always occupies 2s lower energy orbital, instead of 3s higher energy orbital. In other words, Aufbau principle states the incoming electron goes to the orbital, which has least $(n+l)$ value. However, the orbital having lower "n" value will be occupied first, in case any two orbitals have the same $(n+l)$ value.

Activity 4: Hund's Rule, Pauli and Aufbau Principle

1. Please show which electron configuration violates what principles (Aufbau principle, Hund's rule and Pauli principle) and explain the reasons.





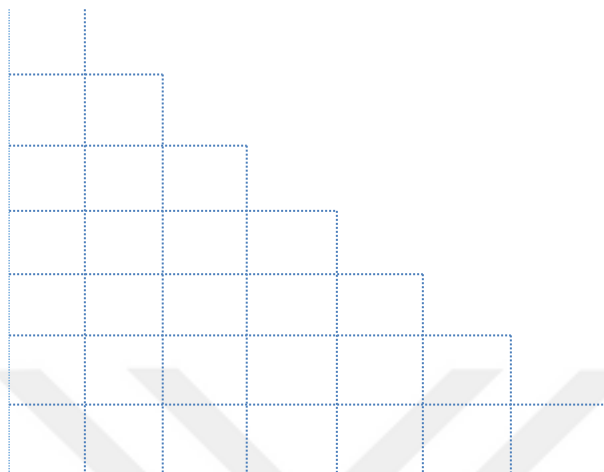
- Using the electron configuration model 1) do an electron configuration for H (# of electron 1), O (# of electron 8), Na (# of electron 11), Cl (# of electron 17).
- Now, you will start writing out the electron configurations for: Al^{+3} , O, Ar, and Ca and fill out the electron spin for each atom by considering Pauli and Aufbau principles.

Al^{+3} (# of e for Al = 13)

Ca (# of e for Ca = 20)

Co^{+2} (# of e for Co = 27)

3. Please use your knowledge on electron configuration to make a table and use vertical lines to determine which subshells correspond with each other:



Activity 4: Different Orbitals Shapes

In this activity, you will make s and p (p_x , p_y , p_z) orbitals' models with different color balloons.

1. After taking 7 balloons (one color for s orbital, 2 different color balloon for p_x orbital, 2 different color balloon for p_y orbitals and, 2 different color balloon for p_z orbitals), you will start creating s and p (p_x , p_y and p_z) orbitals by using the balloons. And draw those orbits here:

S-orbital	p_x - orbital	p_y - orbital	p_z - orbital	All three p orbitals together

2. Now, you will show H, C, F and Al^{+3} orbits by using the models you created.

H	C	F	Al ⁺³

❖ *Readings: Please read Multi-Electron Atoms on pages between 32-35.*

BB Discussion:

1. What can you tell about electron's path around the nucleus?
2. What is Pauli Exclusion Principle telling us? What would happen if Pauli Exclusion principle did not exist?
3. How orbital energy is related to atomic properties?

Lesson 3: Applications

Introduction:

Questions:

1. Where do you see lasers in your everyday experiences?
2. How do you think knowledge about atomic spectrum can inform us about lasers and Neon discharge tubes?
3. Lasers are built based on light's special properties. What do you think these properties are?

Activities:

Activity 1: Laser Simulation

1. Open the simulation by downloading it from the following link:
<https://phet.colorado.edu/en/simulation/lasers>
2. Click on the “One Atom (Absorption and Emission)” tab.
3. Here, you will try to obtain lasing by changing some variables such as light intensity, mirror reflectivity, energy level distance and lifetime. What are the optimum conditions for lasing? Write down the variables you found for optimum lasing.

4. After learning the basic ideas of laser mechanism, you will go on to “Multiple Atoms (Lasing)” tab, and repeat the same observations in the previous step. Write down the variables for optimum lasing.

Activity 2: Neon Lights & Other Discharge Lamps

1. Open the simulation by downloading it from the following link:
<https://phet.colorado.edu/en/simulation/discharge-lamps>
2. Click on the “One Atom” tab.
3. You will make observations by changing the conditions on voltage and the type of atoms.
4. Take 5 observations when you change each variable. What happens to atoms and energy level diagram with single electron?

Type of the Atom	Voltage 1 (V)	Voltage 2 (V)	Voltage 3 (V)	Voltage 4 (V)	Voltage 5 (V)
Hydrogen					
Mercury					
Sodium					
Neon					
Configurable					

5. Now, click on continues electron option and continue your observations. What happens to atoms and energy level diagram with continues electron?

Type of the Atom	Voltage 1 (V)	Voltage 2 (V)	Voltage 3 (V)	Voltage 4 (V)	Voltage 5 (V)
Hydrogen					
Mercury					
Sodium					
Neon					
Configurable					

What are the differences and similarities between single and continues electron options?
And why?

6. Now, you will again take 5 observation records with “Multiple Atoms” tap. (Slow motion button will help you to make accurate observation especially in this section)

Single Electron Production

Type of the Atom	Voltage 1 (V)	Voltage 2 (V)	Voltage 3 (V)	Voltage 4 (V)	Voltage 5 (V)
Hydrogen					
Mercury					
Sodium					
Neon					
Configurable					

Continuous Electron production

Type of the Atom	Voltage 1 (V)	Voltage 2 (V)	Voltage 3 (V)	Voltage 4 (V)	Voltage 5 (V)
Hydrogen					
Mercury					
Sodium					
Neon					
Configurable					

❖ *Readings: Please read Applications section on page 36-39.*

BB Discussion:

1. How can we build lasers that are more efficient?
2. What else can you list as the application of atomic spectra in daily life?

APPENDIX D1. ASSESMENT 1

Assessment 1: The Structure of Atom

Q1) Scientists have proposed many different theories or model for atomic structure by using their experimental observations. What do you think about early atomic models were successful or/and failure to explain certain atomic behaviors?



Q2) In Thomson's experiment, why was the glowing beam repelled by a negatively charged plate?



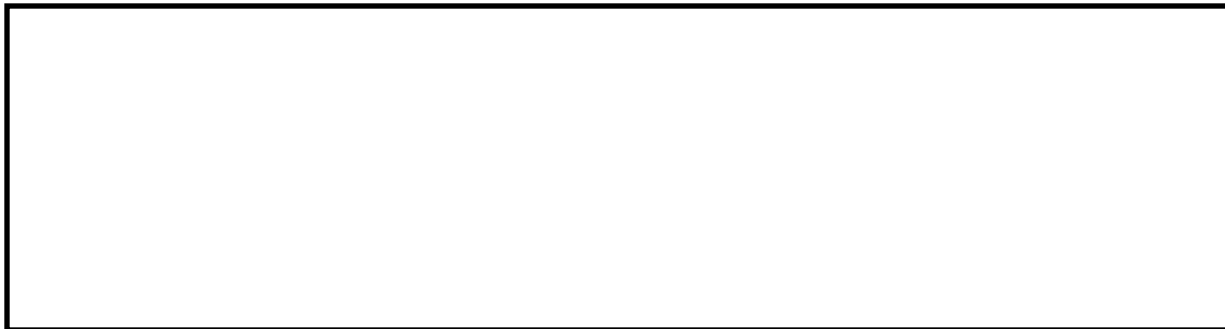
Q3) In Rutherford's experiment, a thin gold foil was bombarded with alpha particles. According to Thomson's "plum-pudding" model of the atom, what should have happened?



Q4) What can you tell about Rutherford's alpha particle scattering experiment and its assertion about atom and nucleus



Q5) Why do you think the proton and electron discovered before the neutron?



Assessment Questions	Activity	Learning Objectives
Q1	L1 A1,2,3,4,5,6	1. Identify and describe particles that comprise atoms. 2. Describe the various models of the atom proposed by early scientists. 3. Describe Thomson's model of the Atom and Rutherford experiment, which disproved it. 4. Discuss Rutherford's planetary model of the atom. State the weaknesses of that model.
Q2	L1 A1,2&3	3. Describe Thomson's model of the Atom and Rutherford experiment, which disproved it.
Q3	L1 A 4&5	3. Describe Thomson's model of the Atom and Rutherford experiment, which disproved it. 4. Discuss Rutherford's planetary model of the atom. State the weaknesses of that model.
Q4	L1 A4&5	3. Describe Thomson's model of the Atom and Rutherford experiment, which disproved it. 4. Discuss Rutherford's planetary model of the atom. State the weaknesses of that model.
Q5	L1 A1,2,3,4,5,6	1. Identify and describe particles that comprise atoms.

APPENDIX D2. ASSESMENT 2

Assessment 2: Energy Quantization

Q1) How can you describe energy states in an atom? What type of energy an electron poses?



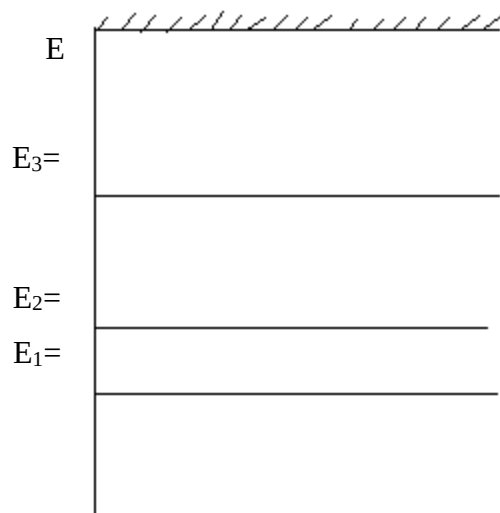
Q2) Briefly describe what is the relation between spectral lines and the energy levels.



Q3) Is there a limit to the number of wavelengths emitted by a certain element? If so, what is it due to? If not, why not?

Q4) How is the energy of a photon related to its frequency? Think about the electromagnetic spectrum. Which color of light has more energy red or blue light? And why?

Q5)

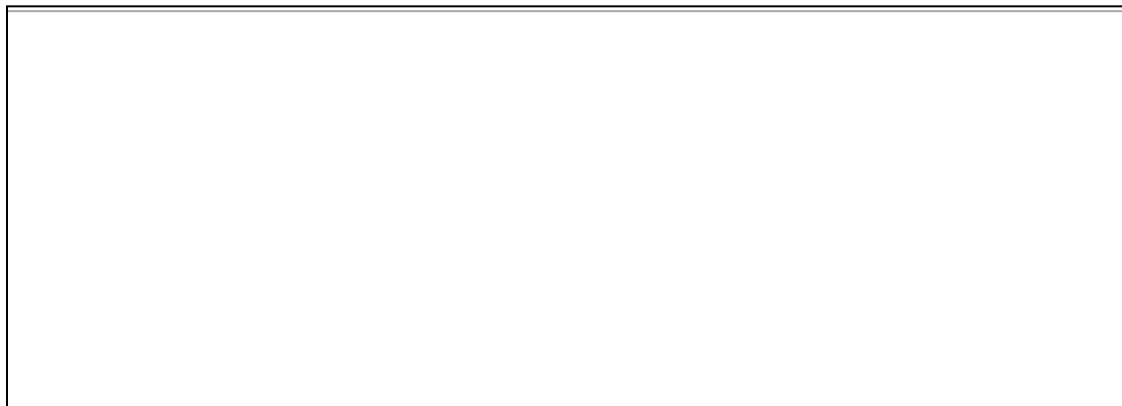


The diagram above shows three energy levels of a hypothetical atom. The lowest available energy level is $E_1 = -5.0 \text{ eV}$

- Draw arrows on the above diagram showing all possible photon emissions for electrons that begin in the 2.2 eV state.
- What wavelength(s) of visible light can electrons emit that begins in the 2.2 eV state?

Q6) Find

- a. The longest wavelength in the Lyman series



- b. The shortest wavelength in the Paschen series.

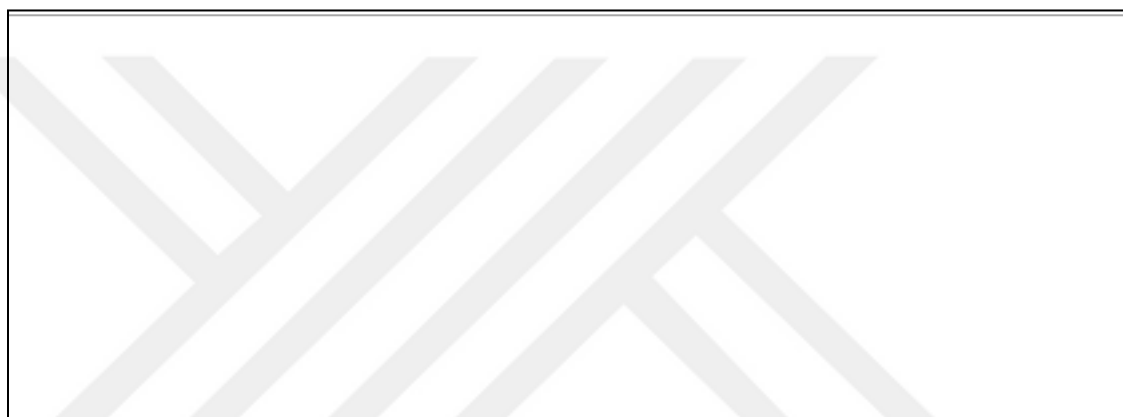


Assessment Questions	Activity	Learning Objectives
Q1	L1 A1&2	1. Understand how energy is quantized. 3. Describe the principle energy levels.
Q2	L1 A1&2	2. Explain the relationships between the line spectrum and the quantized energy levels of an electron
Q3	L1 A1	1. Understand how energy is quantized. 2. Explain the relationships between the line spectrum and the quantized energy levels of an electron 3. Describe the principle energy levels.
Q4	L1A2	1. Know how to calculate the energies of photons emitted in transitions. 2. Given any two among frequency, wavelength, and energy, calculate the third.
Q5	L1 A2	1. Explain the relationships between the line spectrum and the quantized energy levels of an electron 2. Know how to calculate the energies of photons emitted in transitions.
Q6	L1 A2,	1. Explain difference between Lyman, Balmer and Paschen series 2. Given any two among frequency, wavelength, and energy, calculate the third.

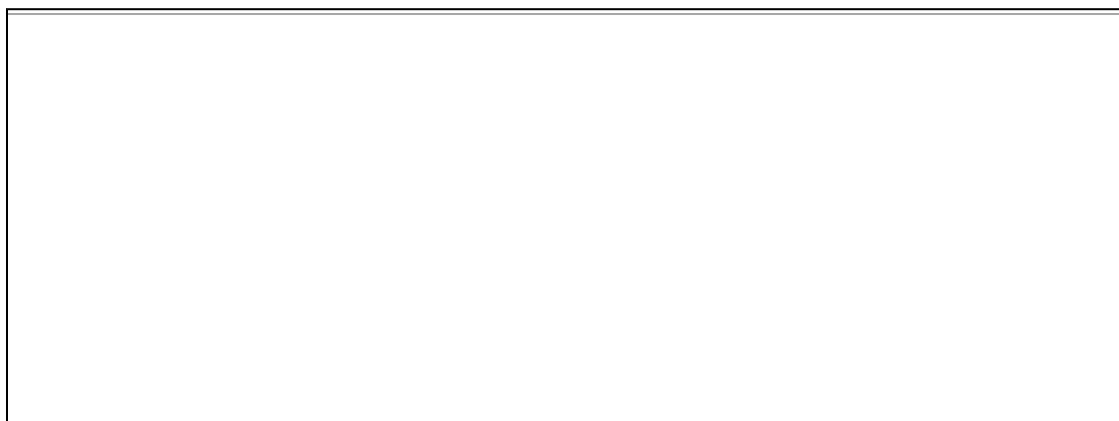
APPENDIX D3. ASSESMENT 3

Assessment 3: Atomic Spectra

Q1) a. How do absorption and emission occur in an atom? Please give details as much as possible.



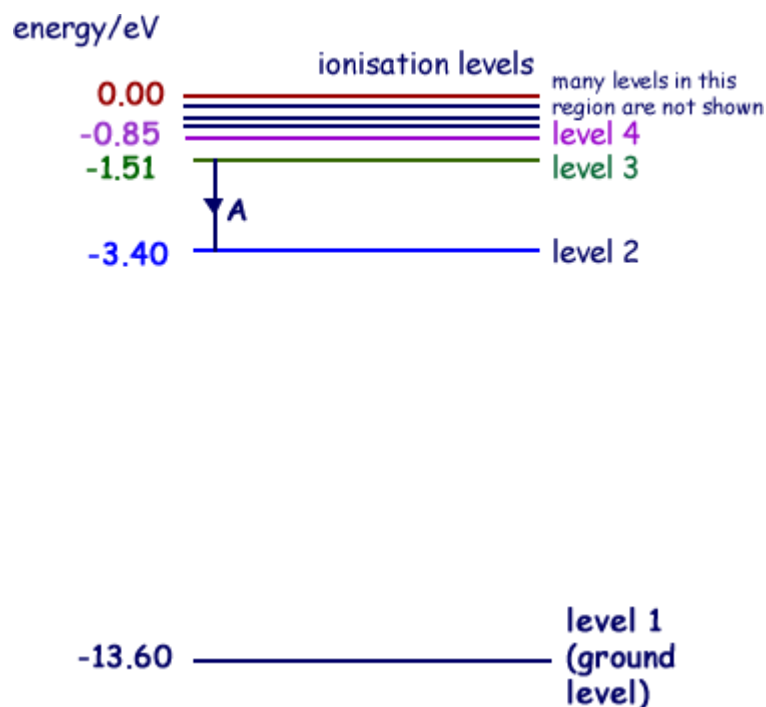
b. A hypothetical atom has 4 energy states. Assuming all transitions are possible, how many spectral lines can this atom produce? And please show the energy level diagram and the transitions here.



Q2) a. What does an absorption spectrum look like? Please sketch the spectrum here. You can use color pencils

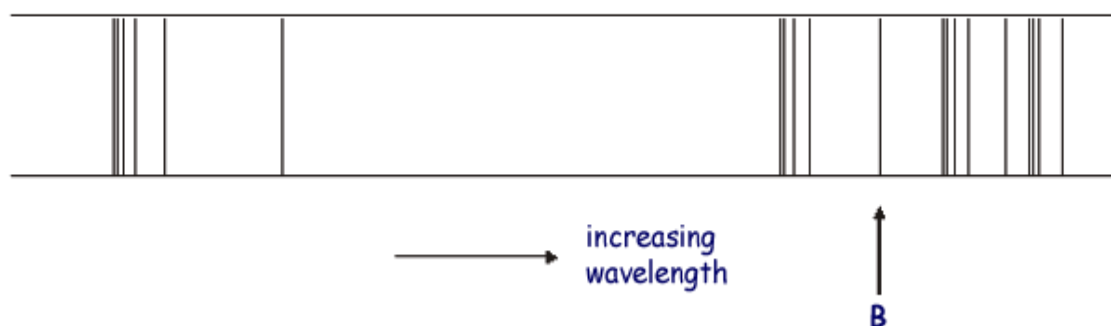
b. What does an emission spectrum look like? Please sketch the spectrum here. You can use color pencils

Q3) The diagram below shows the energy level diagram of a hydrogen atom.



The associated spectrum to the diagram above is shown below. The transition labelled A in the top diagram gives the spectral line labelled B in the spectrum diagram.

Hydrogen spectrum showing some of the main spectral lines



a.

(i) Show that the frequency of spectral line B is about 4.6×10^{14} Hz.

(ii) Calculate the wavelength represented by line B

b. The hydrogen atom is excited and its electron moves to level 4.

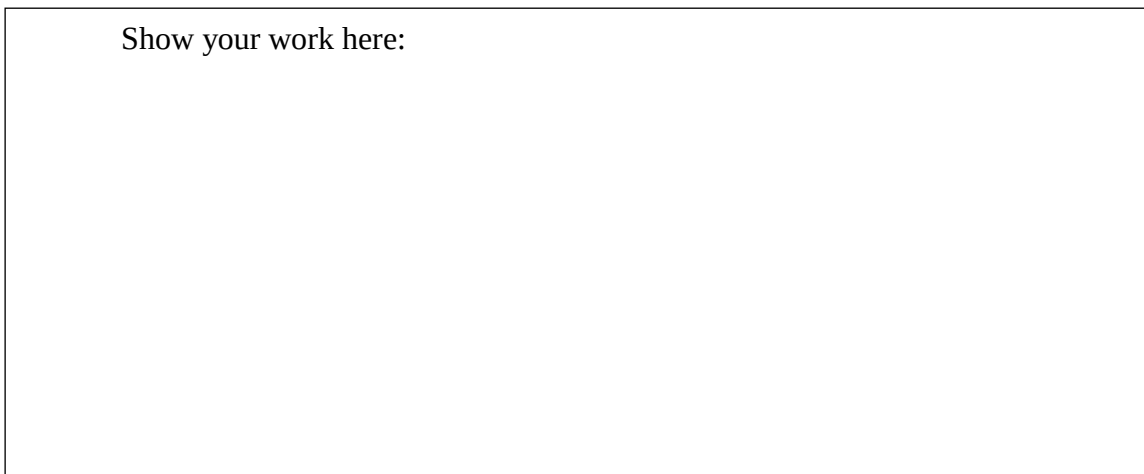
(i) How many different wavelengths of electromagnetic radiation may be emitted as the atom returns to its ground state?

(ii) Calculate the energy, in eV, of the longest wavelength of electromagnetic radiation emitted during this process.



Q4) a. What is the frequency of light emitted when there's a change in energy of $\Delta E = 4.0 \times 10^{-20} \text{ J}$?

Show your work here:

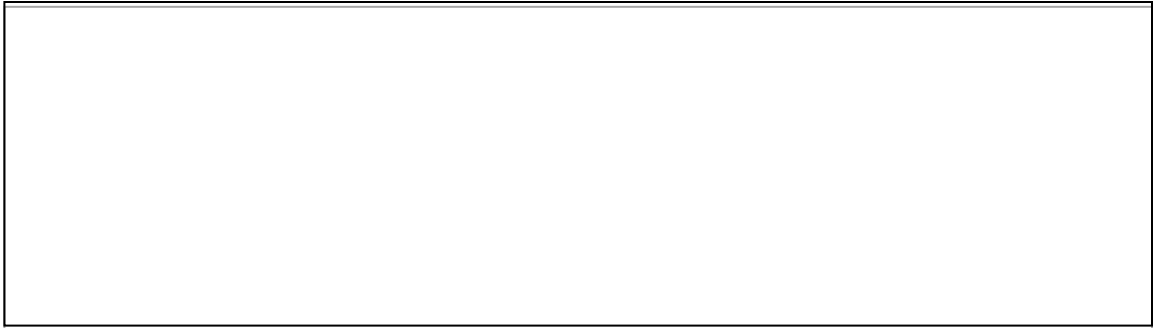


c. What is the change in energy when a 600nm wavelength of light is emitted from an atom? (Planck's constant is $6.626 \times 10^{-34} \text{ J}\cdot\text{s}$)

Show your work here:

Q5) Why do we get all sets of possible transmissions? (i.e. why do electrons sometimes go down to an orbital higher than ground state instead of going straight to ground state?)

Q6) a. Why is information about many stars contained in absorption rather than emission spectra?



b. When you look at the light from the sun and other stars, what type of spectrum you expect to observe? And why?



Assessment Questions	Activity	Learning Objectives
Q1	L2 A1 &2	1. Understand the relationship between atomic energy levels, atomic energy level diagrams, and observed atomic spectra in a discharge lamp. 2. Explain the relation between emission and absorption lines, and what we can learn from these lines. 3. Explain how lines in atomic spectra (absorption or emission) are generated from the absorption of a photon by electrons in the ground state. Explain why electrons will not interact with some photons. 4. Explain how the lines in atomic spectra (absorption or emission) gives evidence that electrons exist only in discrete energy levels. Using electron configuration and the specific energy levels of an atom, explain why each element has a unique emission and absorption spectrum.
Q2	L2 A1	1. Explain the relation between emission and absorption lines, and what we can learn from these lines.
Q3	L2 A1&2	1. Understand the relationship between atomic energy levels, atomic energy level diagrams, and observed atomic spectra in a discharge lamp. 2. Explain how the lines in atomic spectra (absorption or emission) gives evidence that electrons exist only in discrete energy levels. Using electron configuration and the specific energy levels of an atom, explain why each element has a unique emission and absorption spectrum. 3. Given any two among frequency, wavelength, and energy, calculate the third.
Q4	L2 A1&2	1. Explain the relation between emission and absorption lines, and what we can learn from these lines. 2. Given any two among frequency, wavelength, and energy, calculate the third.
Q5	L2 A1&2	1. Understand the relationship between atomic energy levels, atomic energy level diagrams, and observed atomic spectra in a discharge lamp. 2. Explain how lines in atomic spectra (absorption or emission) are generated from the absorption of a photon by electrons in the ground state. Explain why electrons will not interact with some photons. 3. Explain how the lines in atomic spectra (absorption or emission) gives evidence that electrons exist only in discrete energy levels. Using electron configuration and the specific energy levels of an atom, explain why each element has a unique emission and absorption spectrum.

Q6

L2 A1

4. Explain the relation between emission and absorption lines, and what we can learn from these lines.
5. Explain how lines in atomic spectra (absorption or emission) are generated from the absorption of a photon by electrons in the ground state. Explain why electrons will not interact with some photons.
6. Understand how spectra are used to determine the composition of the gases found within a star.



APPENDIX D4. ASSESMENT 4**Assessment 4: Bohr's Model of the Atom**

Q1) a. What was Bohr's reasoning to explain what keeps electrons from striking the nucleus?

b. Write Bohr's quantization rule and explain the terms.

Q2) Radius of the second orbit of lithium atom is $0.70 \times 10^{-10} \text{ m}$. What would be the radius of the fourth orbit of lithium atom?

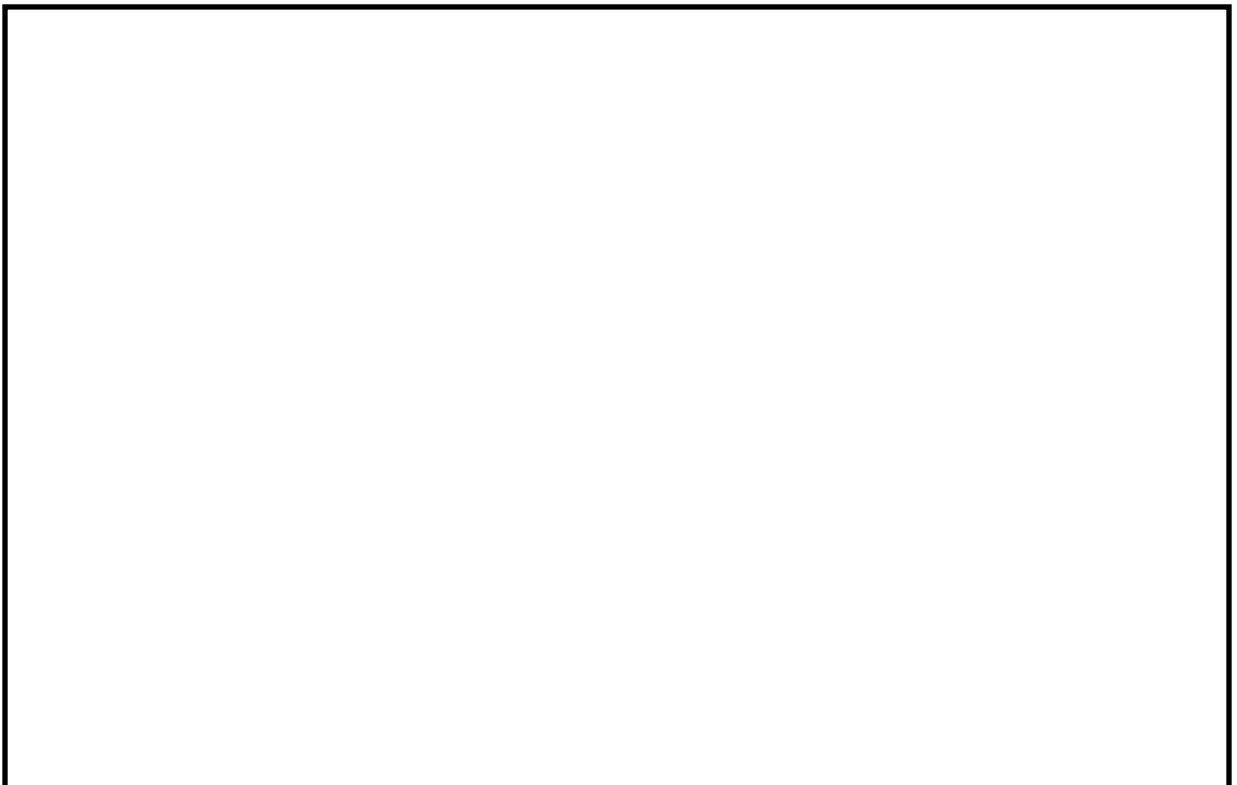
Q3) Obtain an expression for the radius of the n^{th} orbit of an electron in hydrogen-like atoms. Draw a graph between the radius of the orbit and the energy levels for the hydrogen atom.



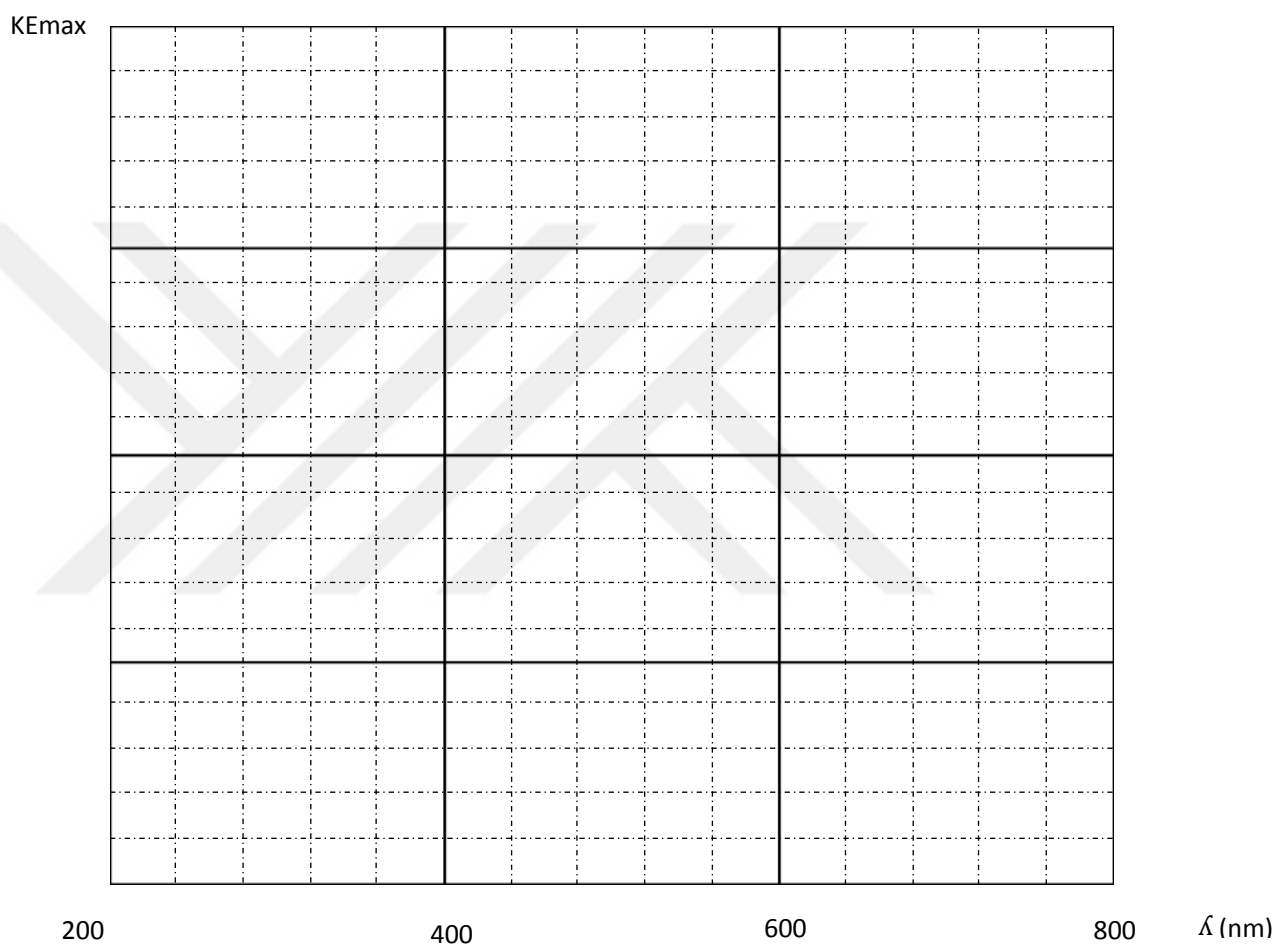
Q4) Write down an expression for the Bohr radius a_0 , (a) in terms of e , ϵ_0 , $\hbar$, m



Q5) State Bohr's assumptions for hydrogen like atoms. Do any of those postulates contradict with classical physics results? And Why?



Q6) On the axes below, sketch a graph of the maximum kinetic energy $KE_{\max}$ of ejected electrons as a function of the wavelength λ of the incident light for the range of wavelengths indicated. Label the vertical axis with an appropriate scale and units.



Assessment Questions	Activity	Learning Objectives
Q1	L1 A1&2	1. Describe Bohr's planetary model of the atom. 2. Know the two assumptions of the Bohr model and be able to apply those assumptions in order to find the energy levels and orbital radii of the Bohr model for hydrogen and single electron atoms. 3. Explain that Niels Bohr proceed a model of the hydrogen atom based on experimental observations. This model indicates that: I. An electron cycles the nucleus only in fixed energy ranges called orbit II. An electron can neither gain nor lose energy inside this orbit, but could move up or down to another orbit. III. That the lowest energy orbit is closest to the nucleus.
Q2	L1 A1	1. Know the two assumptions of the Bohr model and be able to apply those assumptions in order to find the energy levels and orbital radii of the Bohr model for hydrogen and single electron atoms.
Q3	L1 A1	1. Describe Bohr's planetary model of the atom. 2. Know the two assumptions of the Bohr model and be able to apply those assumptions in order to find the energy levels and orbital radii of the Bohr model for hydrogen and single electron atoms.
Q4	L1 A	1. Describe Bohr's planetary model of the atom. 2. Know the two assumptions of the Bohr model and be able to apply those assumptions in order to find the energy levels and orbital radii of the Bohr model for hydrogen and single electron atoms.
Q5	L1 A1&2	1. Describe Bohr's planetary model of the atom. 2. Know the two assumptions of the Bohr model and be able to apply those assumptions in order to find the energy levels and orbital radii of the Bohr model for hydrogen and single electron atoms. 3. Explain that Niels Bohr proceed a model of the hydrogen atom based on experimental observations. This model indicates that: I. An electron cycles the nucleus only in fixed energy ranges called orbit II. An electron can neither gain nor lose energy inside this orbit, but could move up or down to another orbit. III. That the lowest energy orbit is closest to the nucleus.
Q6	L1 A2	1. Know the two assumptions of the Bohr model and be able to apply those assumptions in order to find the energy levels and orbital radii of the Bohr model for hydrogen and single

electron atoms.

2. Explain that Niels Bohr proceed a model of the hydrogen atom based on experimental observations. This model indicates that:
 - I. An electron cycles the nucleus only in fixed energy ranges called orbit
 - II. An electron can neither gain nor lose energy inside this orbit, but could move up or down to another orbit.
 - III. That the lowest energy orbit is closest to the nucleus.

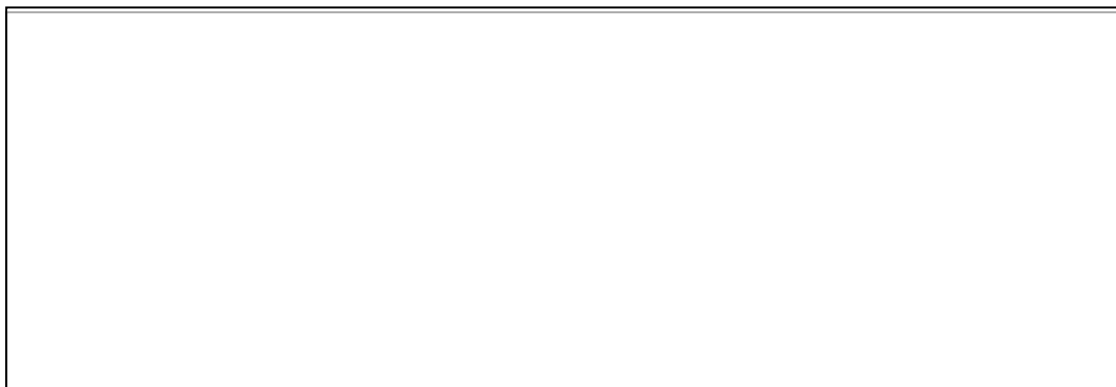


APPENDIX D5. ASSESMENT 5**Assessment 5: Wave Mechanics and the Hydrogen Atom
(QM Hydrogen Atom)**

Q1) a. What was de Broglie's hypothesis about standing waves? And how de Broglie's theory inspired Niels Bohr to revise his atom model?



b. What is the wavelength of the musical note A = 460 hz when it is propagated through air in which the velocity of sound is 343 m s^{-1} ?



Q2) Use de Broglie's wave-particle duality and the Heisenberg uncertainty principle to explain why the location of an electron in an atom is uncertain.

Q3) a. What is the maximum number of orbitals with:

$n = 4 \quad l = 1$ _____
(Explain_____)

$n = 2 \quad l = 2$ _____
(Explain_____)

$n = 3 \quad l = 2$ _____
(Explain_____)

$n = 5 \quad l = 1 \quad m_l = -1$ _____
(Explain_____)

b. Answer following questions:

p orbitals have an azimuthal quantum number (L) of:

d orbitals have an azimuthal quantum (L) number of

There are how many values of m_L are there for $L = 2$ (d orbitals)

What is the Principle Quantum number (n) of the first shell to have d orbitals?

Q4) a. What does the Schrödinger equation represent?

b. A wavefunction is

Q5) What is the main difference between Bohr's model of the atom and the atomic theory that is currently accepted?



Q6) Now based on all the information you have what would you say about an electron? Is it wave? particle or what?

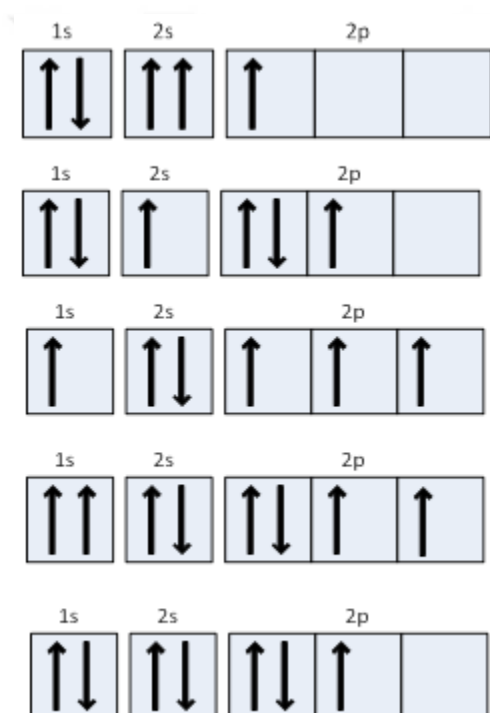


Assessment Questions	Activity	Learning Objectives
Q1	L1 A2	1. Describe the theories of de Broglie, Schrodinger, and Heisenberg, and explain how their work led to a revised understanding of the atom, electrons, and light. 2. Know the definition of the de Broglie wavelength, and how this leads to an improvement on the Bohr model 3. Explain how the quantum mechanical model is based upon the idea that electrons travel in waves.
Q2	L1 A2	1. Describe the theories of de Broglie, Schrodinger, and Heisenberg, and explain how their work led to a revised understanding of the atom, electrons, and light. 2. Know the definition of the de Broglie wavelength, and how this leads to an improvement on the Bohr model 3. Explain how the quantum mechanical model is based upon the idea that electrons travel in waves.
Q3	L1 A1	1. Explain that the quantum state of the electron in an atom can be described by four quantum numbers (n, l, m, s) 2. Describe how to write the electron configuration for an atom has single electron.
Q4	L1A3	1. Use knowledge on Newtonian mechanics to be able to derive time independent Schrodinger equation.
Q5	L1 A1,2&3	1. Describe the theories of de Broglie, Schrodinger, and Heisenberg, and explain how their work led to a revised understanding of the atom, electrons, and light. 2. Explain how the quantum mechanical model is based upon the idea that electrons travel in waves. 3. Explain that the quantum state of the electron in an atom can be described by four quantum numbers (n, l, m, s) 4. Describe how to write the electron configuration for an atom has single electron. 5. Use knowledge on Newtonian mechanics to be able to derive time independent Schrodinger equation.
Q6	L1 A1,2 &3	1. Describe the theories of de Broglie, Schrodinger, and Heisenberg, and explain how their work led to a revised understanding of the atom, electrons, and light. 2. Explain how the quantum mechanical model is based upon the idea that electrons travel in waves. 3. Explain that the quantum state of the electron in an atom can be described by four quantum numbers (n, l, m, s) 4. Describe how to write the electron configuration for an atom has single electron. 5. Use knowledge on Newtonian mechanics to be able to derive time independent Schrodinger equation.

APPENDIX D6. ASSESSMENT 6

Assessment 6: Multiple Electron and Applications

Q1) Please write which of the rules (Aufbau principle, the Pauli Exclusion Principle, Hund's Rule) do each of the following electron energy diagrams violate?



Because

Because

Because

Because

Because

1 H Hydrogen 1.00794																	2 He Helium 4.003						
3 Li Lithium 6.941	4 Be Beryllium 9.012182																	5 B Boron 10.811	6 C Carbon 12.0107	7 N Nitrogen 14.00674	8 O Oxygen 15.9994	9 F Fluorine 18.9984032	10 Ne Neon 20.1797
11 Na Sodium 22.989770	12 Mg Magnesium 24.3050																	13 Al Aluminum 26.981538	14 Si Silicon 28.0855	15 P Phosphorus 30.973761	16 S Sulfur 32.066	17 Cl Chlorine 35.4527	18 Ar Argon 39.948
19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.955910	22 Ti Titanium 47.867	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.938049	26 Fe Iron 55.845	27 Co Cobalt 58.933200	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.723	32 Ge Germanium 72.61	33 As Arsenic 74.92160	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.80						
37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90585	40 Zr Zirconium 91.224	41 Nb Niobium 92.90638	42 Mo Molybdenum 95.94	43 Tc Technetium (98)	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.90550	46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.760	52 Te Tellurium 127.60	53 I Iodine 126.90447	54 Xe Xenon 131.29						
55 Cs Cesium 132.90545	56 Ba Barium 137.327	57 La Lanthanum 138.9055	72 Hf Hafnium 178.49	73 Ta Tantalum 180.9479	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.078	79 Au Gold 196.96655	80 Hg Mercury 200.59	81 Tl Thallium 204.3833	82 Pb Lead 207.2	83 Bi Bismuth 208.98038	84 Po Polonium (209)	85 At Astatine (210)	86 Rn Radon (222)						
87 Fr Francium (223)	88 Ra Radium (226)	89 Ac Actinium (227)	104 Rf Rutherfordium (261)	105 Db Dubnium (262)	106 Sg Seaborgium (263)	107 Bh Bohrium (262)	108 Hs Hassium (265)	109 Mt Meitnerium (266)	110 (269)	111 (272)	112 (277)	113	114										

Q2) Write the complete electron configurations for the elements below by using the periodic table given above.

He:

V :

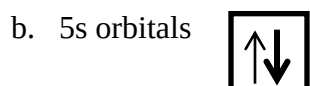
Ni:

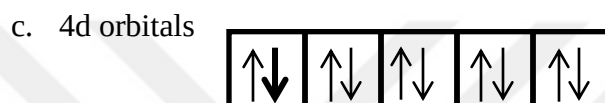
Cu:

Br:

Q3) Write the values for the quantum numbers for the bold electron in the following diagrams:



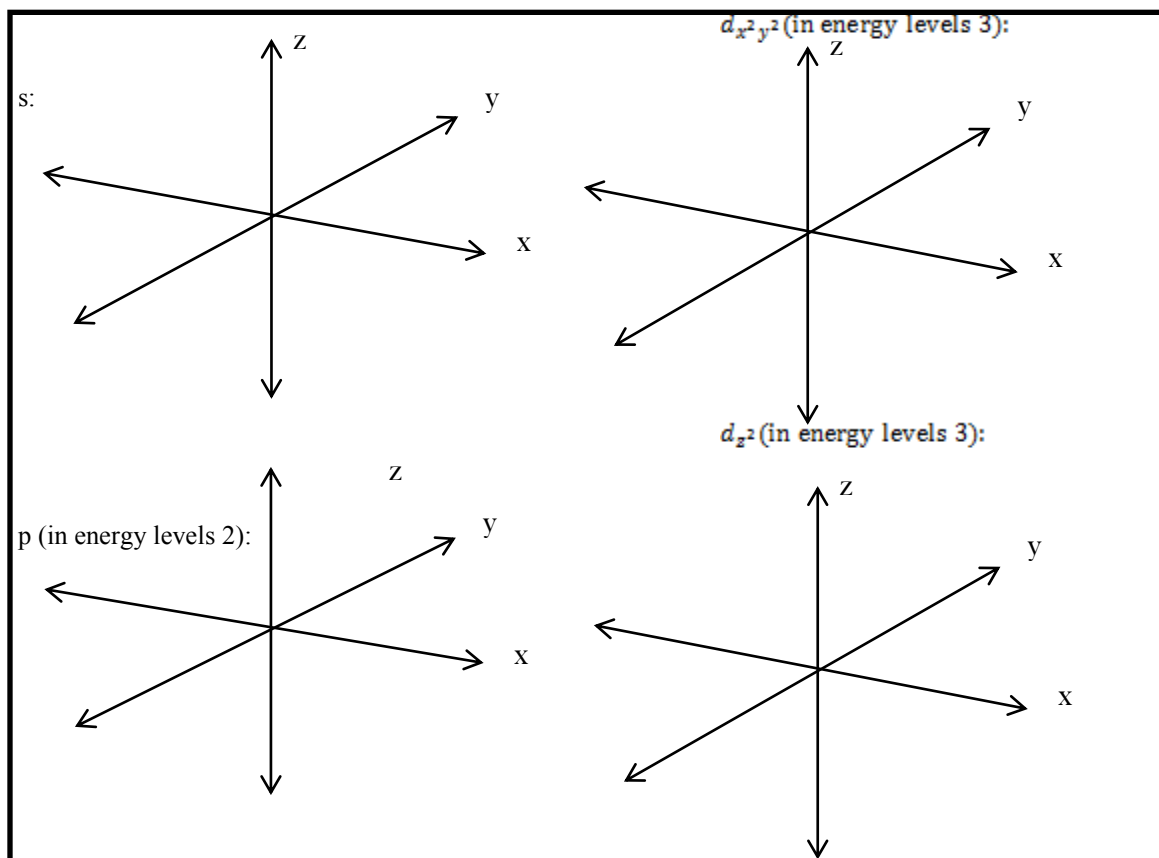






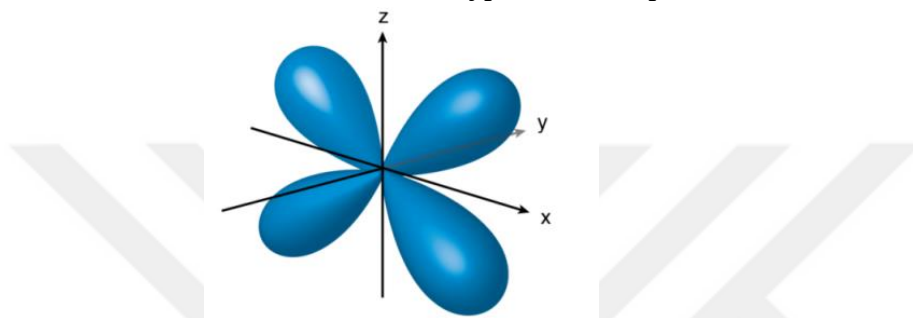
Q4)

a. Draw a picture for an *s*-orbital, *p*-orbital, *d*-orbital



b. How many f orbital orientations are there?

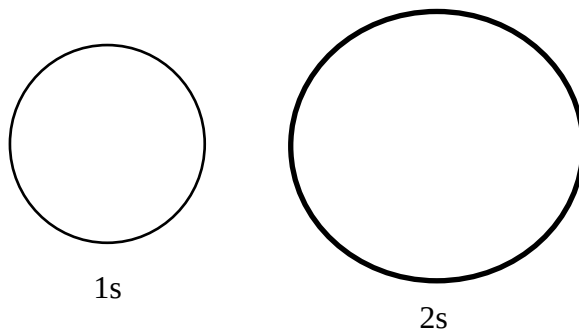
c. What is the ℓ value for the type of orbital pictured below? And why?



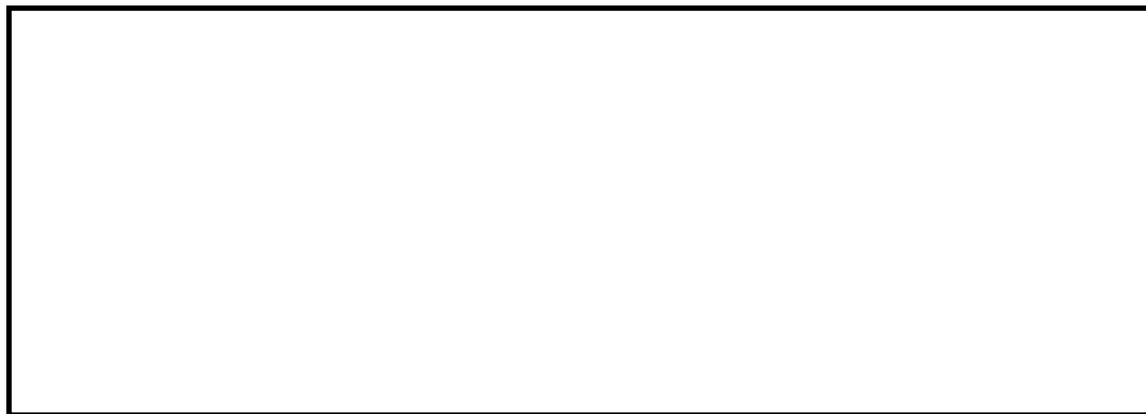
Q5) a. Why the probability of density is higher in the area that is closer to the nucleus?

a. What is the difference between the terms orbit and orbital?

- b. Plot the probability density for 1s and 2s orbitals and explain your plots with the reasons.



- Q6) a. How do low-level lasers work? You can support your explanations with drawings



- b. In a fluorescent tube, explain how the mercury vapor and the coating of its inner surface contribute to the production of visible light.



Assessment Questions	Activity	Learning Objectives
Q1	L2 A1,2&3	1. State the maximum number of orbitals and electrons found in each sub-level. 2. Apply the Pauli Exclusion Principle, Hund's Rule and Aufbau Principles to write electron configurations using orbital diagrams, and electron configuration. 3. Explain the organization of energy levels, sub-levels (s, p, d, and f), and orbitals in atoms.
Q2	L2 A3	1. State the maximum number of orbitals and electrons found in each sub-level. 2. Use quantum numbers to label shells, subshells, and orbitals. 3. Apply the Pauli Exclusion Principle, Hund's Rule and Aufbau Principles to write electron configurations using orbital diagrams, and electron configuration. 4. Explain the organization of energy levels, sub-levels (s, p, d, and f), and orbitals in atoms. 5. State the relationship between the principle quantum number (n), the number of orbitals, and the maximum number of electrons in a principle energy level.
Q3	L1 A3	1. Use quantum numbers to label shells, subshells, and orbitals. 2. Explain the organization of energy levels, sub-levels (s, p, d, and f), and orbitals in atoms. 3. State the relationship between the principle quantum number (n), the number of orbitals, and the maximum number of electrons in a principle energy level.
Q4	L2 A4	1. Be able to draw s, p, and d orbitals.
Q5	L2 A2&3&4	1. State the maximum number of orbitals and electrons found in each sub-level. 2. Explain the organization of energy levels, sub-levels (s, p, d, and f), and orbitals in atoms. 3. State the relationship between the principle quantum number (n), the number of orbitals, and the maximum number of electrons in a principle energy level. 4. Be able to draw s, p, and d orbitals. 5. Explain the concepts of orbital, electron density, and probability as used in the model of the atom
Q6	L3 A1&2	1. Describe how a laser works. 2. Know the three important characteristics of laser light that distinguishes it from light produced by other light sources such as an incandescent bulb (or the sun). 3. Explain how a fluorescent tube works 4. Explain how energy is transferred in each process involved in discharge lamps. 5. Use knowledge of energy levels and atomic spectrums to explain real-life application.

APPENDIX E. QUANTUM MECHANICS LEARNING EXIT SURVEY

Quantum Mechanics Learning Exit Survey

		Strongly Disagree	Disagree	Not Decided	Agree	Strongly Agree
	Question					
1	I understood everything in today's session					
2	I am leaving still unsure about today's lesson					
3	I understood the key ideas we have covered in this unit					
4	Activities were useful to visualize the quantum mechanics phenomena					
5	I engaged with activities well today					
6	Models that I engaged today were useful to understand the concepts					
7	I did not understand the relationships today's activities with and the quantum concepts					
8	The models that we used in the lesson helped me change my previous model					
9	These activities were too time-consuming.					
10	This lesson offers valuable information that I'll be able to use in my future learning.					

What part of the learning activity helped you the most on your learning? Why?

What is still the most challenging part and why?

What do you think about the format of this class?

APPENDIX F. TRADITIONAL COMPUTER-BASED SIMULATION INSTRUCTION STUDENT WORKSHEET

CHAPTER 1: EARLY MODELS OF ATOM

- ❖ *Readings: Please read The Thomson and Rutherford atom models on page 1 & 2 (Until Planetary Model on Page 2)*

Pre Activity Task: Write a short summary about The Thomson Model and The Rutherford Model based on what you read and what you know. Please be explicit as much as possible.

Activity 1: Plum Pudding Atom

- 1- Open the simulation by clicking the following link:
<https://phet.colorado.edu/en/simulation/rutherford-scattering>
- 2- Download and open the simulation.
- 3- Start with “Plum Pudding Atom” tab
- 4- Please take notes what are your observations about Thomson atomic model when you change the variables? You can also draw pictures to support your idea.



Activity 2: Rutherford Atom

- 1- Open the simulation by clicking the following link:
<https://phet.colorado.edu/en/simulation/rutherford-scattering>
- 2- Click on “Rutherford Atom” tab
- 3- Please take notes what are your observations about Rutherford atomic model when you change the variables? You can also draw pictures to support your idea.



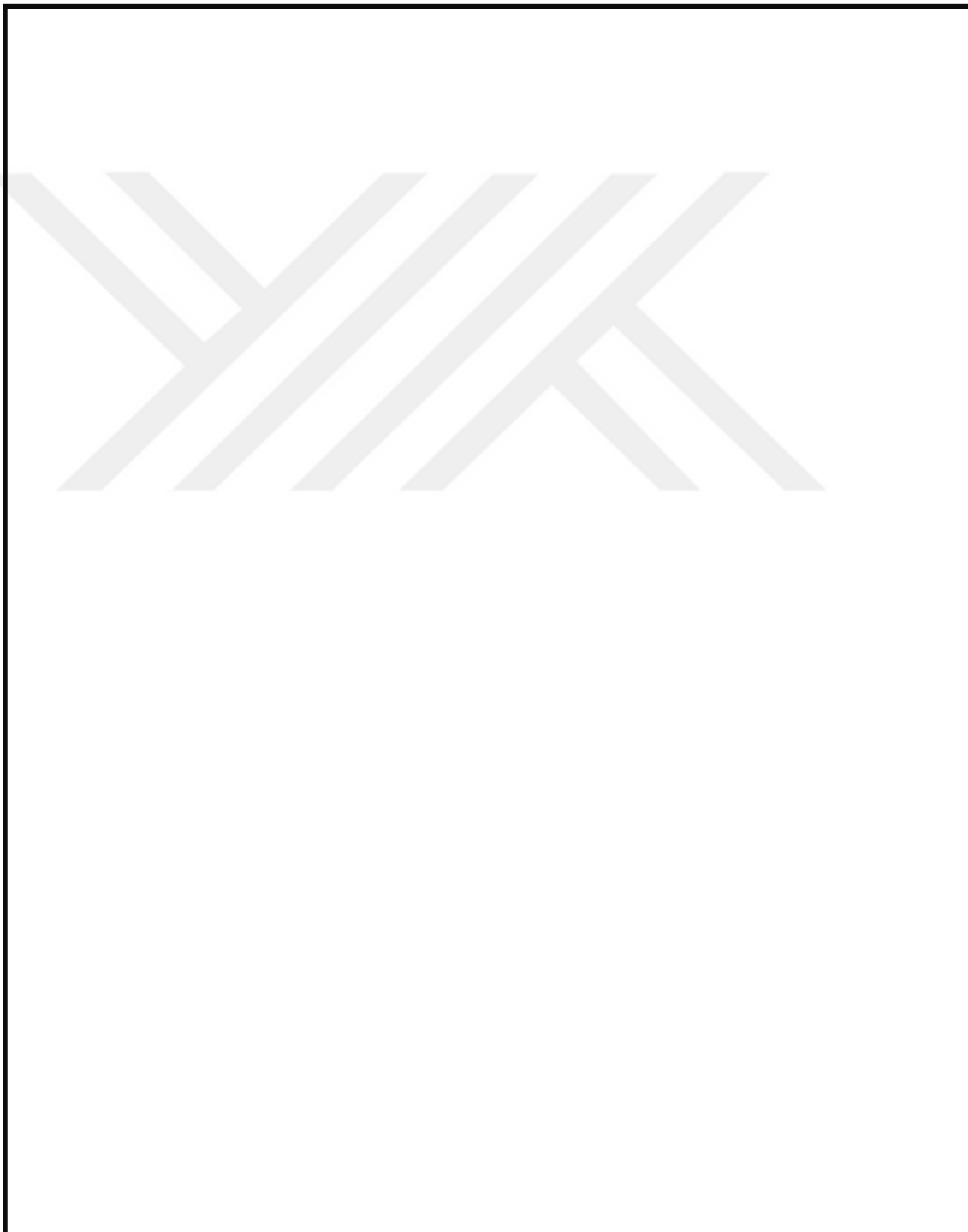
❖ *Readings: Please read The Planetary Model on page 2-4*

Pre Activity Task: Write a short summary about The Planetary Model based on what you read and what you know. Please be explicit as much as possible.



Activity 3: The Planetary (Solar System) Model

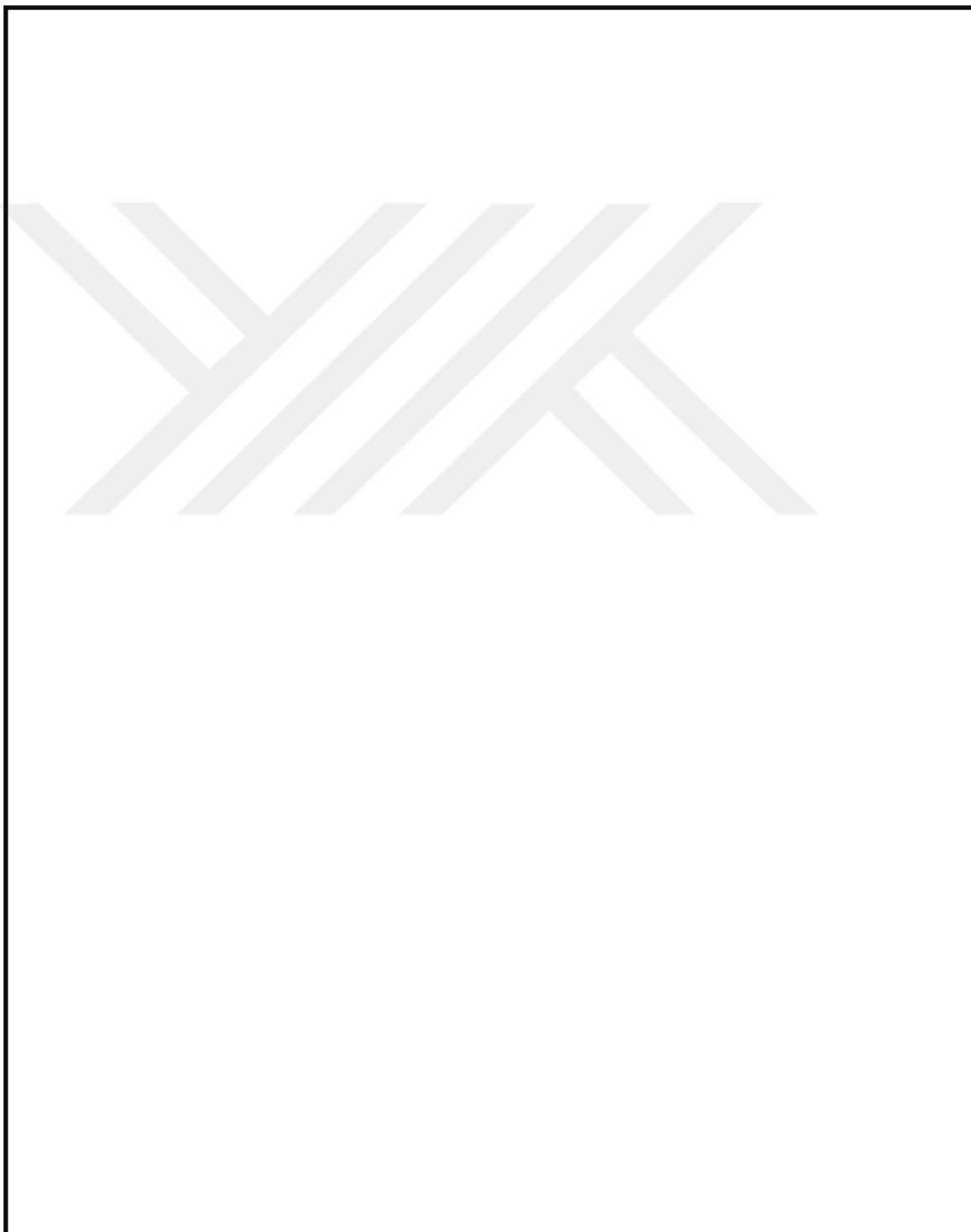
1. Open the simulation by clicking the following link:
<https://phet.colorado.edu/en/simulation/hydrogen-atom>
2. Click on “Classical Solar System” tab
3. Explain the motion of electron according to planetary model. You can also draw pictures and make calculations to support your idea.



CHAPTER 2: ENERGY QUANTIZATION

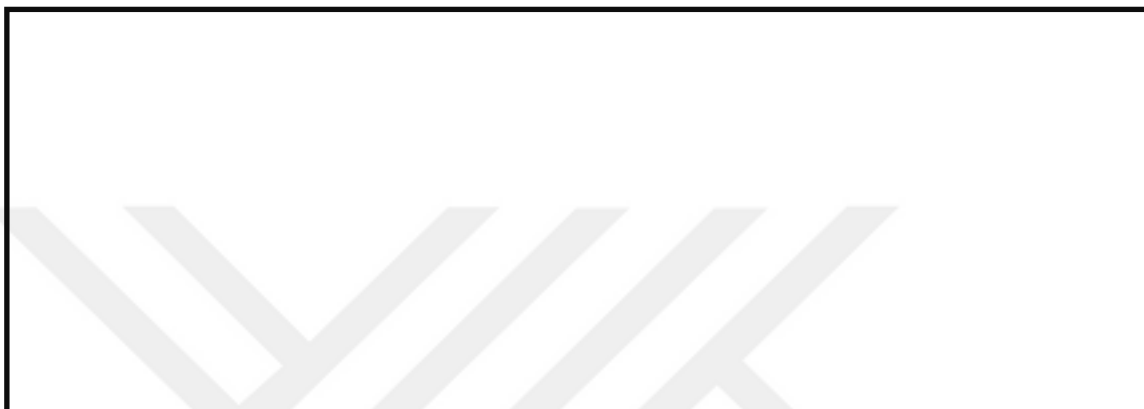
❖ *Readings: Please read The Energy Quantization chapter on page 5-12*

Pre Activity Task: Write a short summary about The Energy Quantization based on what you read and what you know. Please be explicit as much as possible.



Activity 4: Hydrogen spectroscopy

1. Open the simulation by clicking the following link:
<http://phys.educ.ksu.edu/vqm/free/h2spec.html>
2. Follow the steps from 1 to 4 on the simulation page:
 - What is your general observation on the actual gas spectrums? Please write down a detailed explanation about your observations



- What is your observation on spectral lines? How did you match the spectral lines and what can you tell about actual gases spectral lines? Please write down a detailed explanation about your observations



Activity 5: Energy levels and Photon absorption of Hydrogen atom

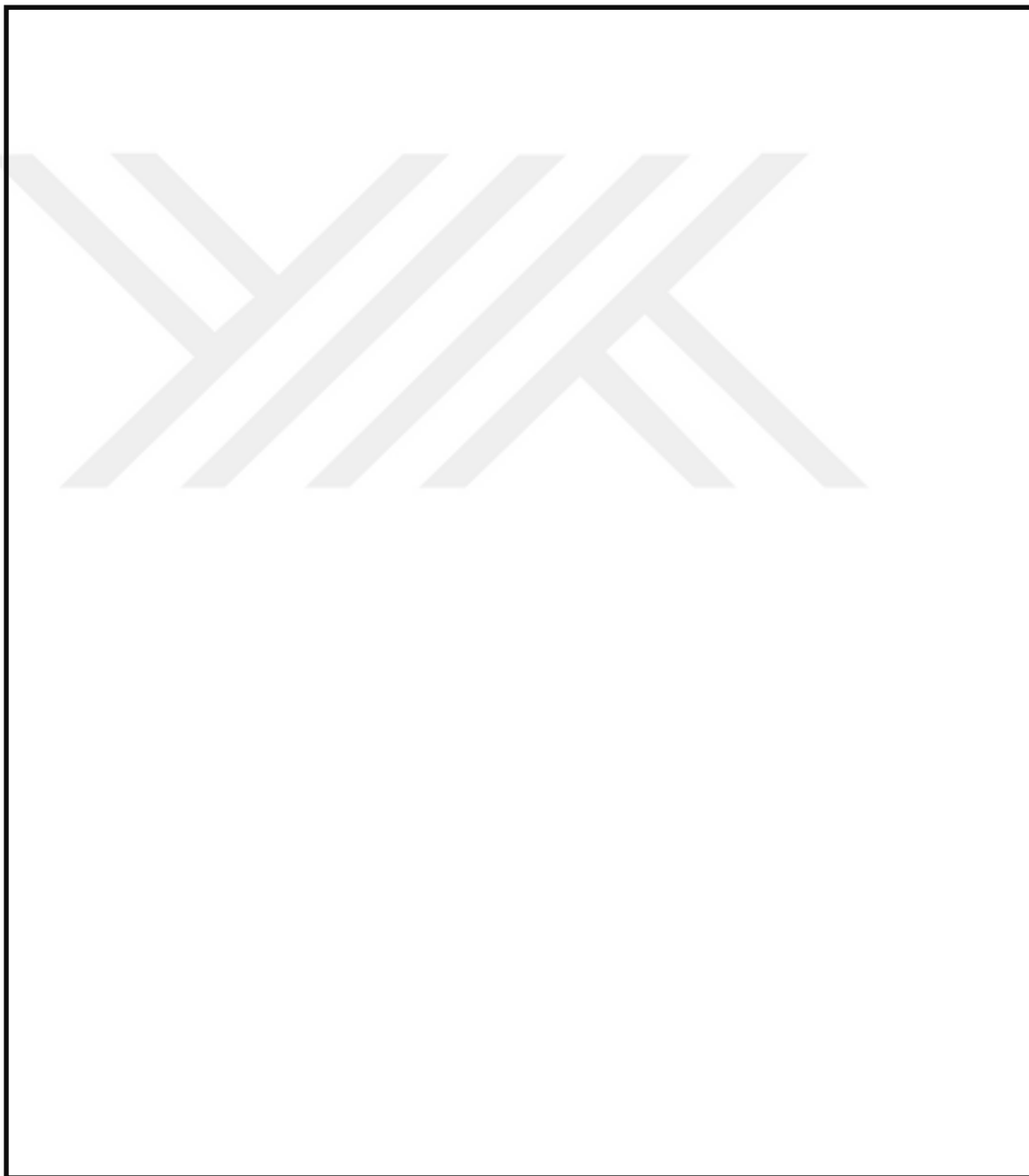
1. Open the simulation by clicking the following link:
http://astro.unl.edu/naap/hydrogen/animations/hydrogen_atom.html
2. Use the Photon Selection panel to fire a photon at the atom. Pressing the fire photon button will fire a photon with the energy selected by the slider. The Energy Level Diagram panel provides an alternate representation of the atom's state, showing how the energy needed to ionize the atom depends on which level electron is in. The Event Log provides a history of the events in the simulator. The most recent entries are added at the bottom.
3. Now, you will make observation on electron transition in a hydrogen atom. Please write down your observations and explain what happens when you change the variables.



CHAPTER 3: ATOMIC SPECTRA

❖ *Readings: Please read Atomic spectra chapter on page 13-21*

Pre Activity Task: Write a short summary about Atomic line spectra and energy levels, absorption and emission based on what you read and what you know. Please be explicit as much as possible.



Activity 6: Simulation: Atomic Absorption and Emission

1. Open the simulation by copying & pasting the following link:
http://www.cengage.com/chemistry/book_content/0495012017_skoog/student_website/as_ie2.html
2. Click “Atomic spectra” link, which is located under “An Introduction to Optical Atomic Spectroscopy” section.
3. Read the instruction on the simulation page and make observations by sending photon with different wavelengths



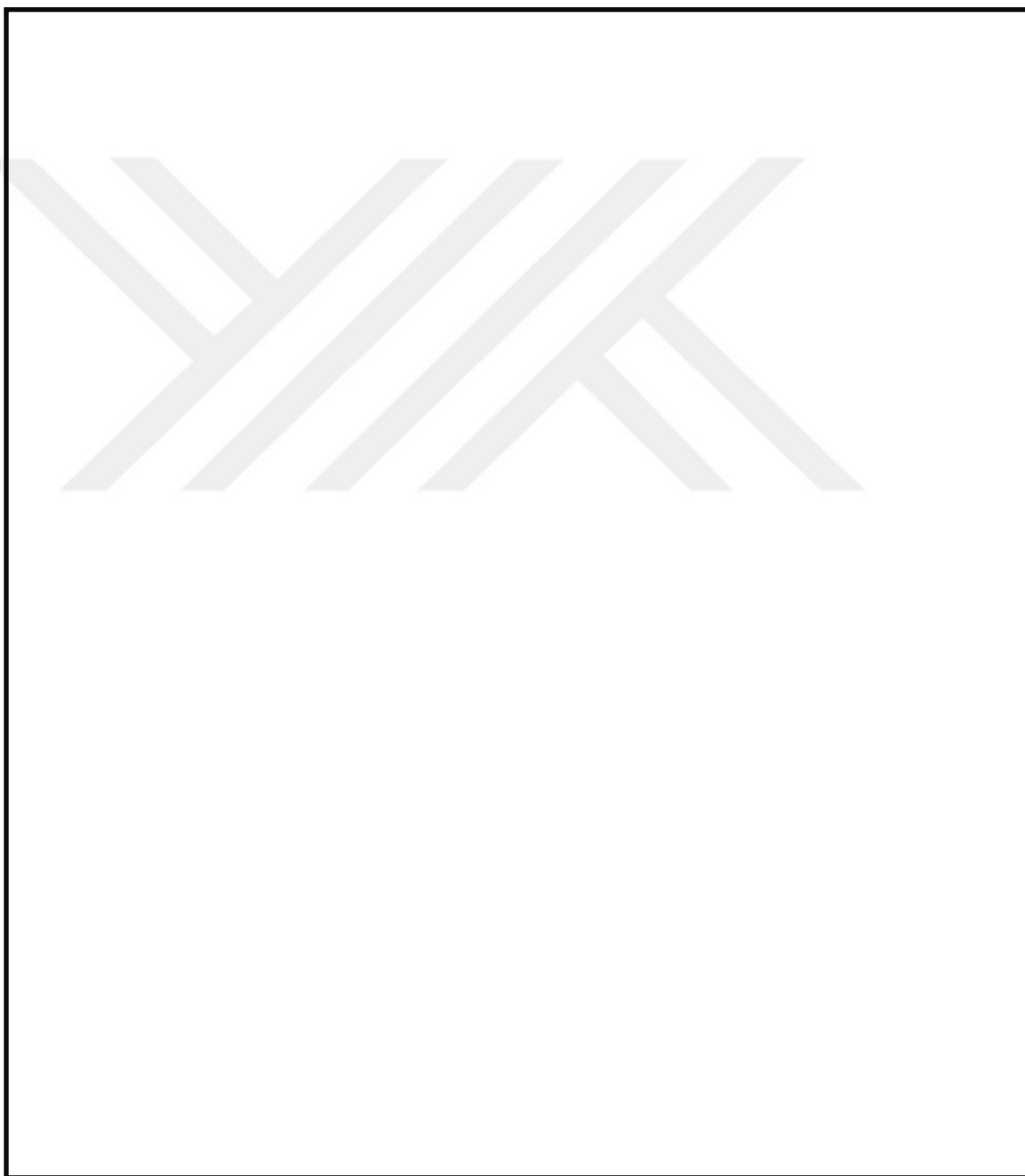
4. After completing observations, click “continue” button and answer following 9 questions.
5. What do you learn about hydrogen atom and electron transition of hydrogen atom?



CHAPTER 4: BOHR ATOM MODEL

❖ *Readings: Please read Bohr Atom Model chapter on page 22-28*

Pre Activity Task: Write a short summary about Bohr Atom model, Assumptions of the Bohr model, Bohr Orbits, Energy of the Bohr orbits and hydrogen spectrum based on what you read and what you know. Please be explicit as much as possible. Please also calculate the Bohr radius.



Activity 7: The Bohr Atom Model

5. Open the simulation by clicking the following link:
http://highered.mheducation.com/olcweb/cgi/pluginpop.cgi?it=swf::800::600::sites/dl/free/0072482621/59229/Bohr_Nav.swf::The%20Bohr%20Atom
6. You will play with radius of the atom model and observe how emission lines are located by making electron jump from higher energy levels to lower ones. Please write down your observations and describe how emission lines change with the radius?



7. Now calculate the Bohr Radius and solve it for the 1st and second energy levels for Hydrogen atom

Hint: The angular momentum of the electron must be a nonzero integer $h/2\pi$. Since e moves with a speed v in a circular path of radius r , its angular momentum $L = rmv$.

The condition for n th allowed orbits will be $L_n = r_n m v_n = nh/2\pi$

Bohr Radius:

r_1 (for H):

r_2 (for H):

CHAPTER 5: WAVE MECHANICS (QUANTUM ATOM MODEL)

❖ *Readings: Please read Wave Mechanics parts on page 29-35*

Pre Activity Task: Write a short summary about Wave Mechanics and the Hydrogen Atom, quantum numbers, electron shells, probability distribution, multi electron atoms, Pauli exclusion principle and electron configuration based on what you read and what you know. Please be explicit as much as possible. Please also give examples for electron configurations.

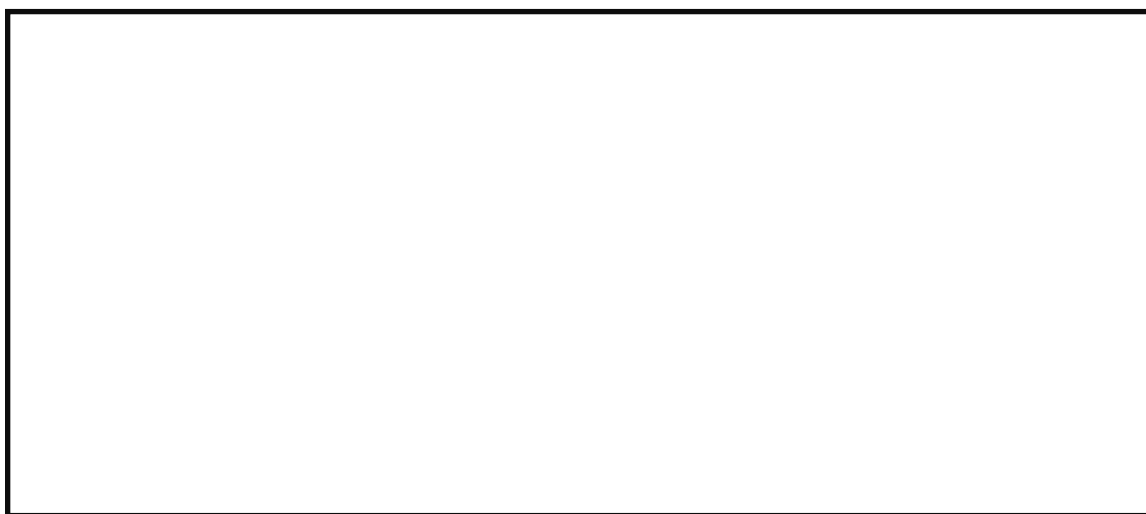


Activity 8: Quantum Models of Hydrogen Simulation (de Broglie and Schrodinger models)

1. Open the simulation by downloading it from the following link:
<https://phet.colorado.edu/en/simulation/hydrogen-atom>
2. Click on “de Broglie” tab
3. You will start with de Broglie model. Clicking on “Experiment”, you will observe what happens when light is shot at the hydrogen atom.
4. Then, you will turn on the “prediction” and make couple more observation by changing the light to monochromatic light, and record the changes



5. After completing your observation on de Broglie wave model, repeat the same process with Schrodinger atom model. You can also see electron energy level on the right side of the screen. Please write down your observations



6. Find the relationship between frequency and wavelength



7. Find the wavelength of a particle that has 560Hz frequency.



CHAPTER 6: MULTI-ELECTRON ATOMS

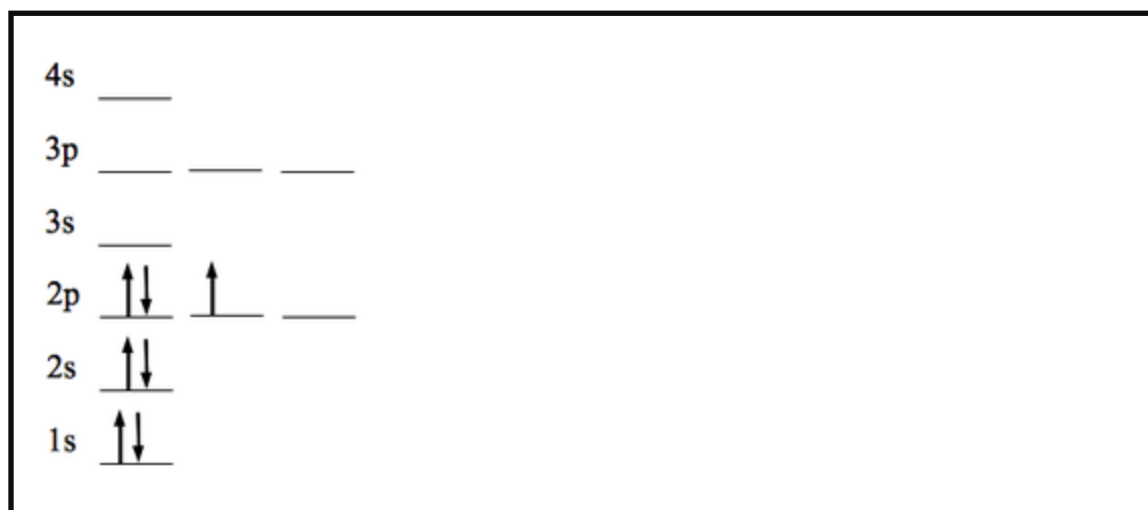
❖ *Readings: Please read Applications parts on page 36-39*

Pre Activity Task: Write a short summary about Multi-Electron Atoms, The Pauli Principle, The Aufbau Principle and electron configuration based on what you read and what you know. Please be explicit as much as possible. Please also give examples for electron configurations.



Activity 1: Hund's Rule, Pauli and Aufbau Principle

1. Please show which electron configuration violets what principles (Aufbau principle, Hund's rule and Pauli principle) and explain the reasons.

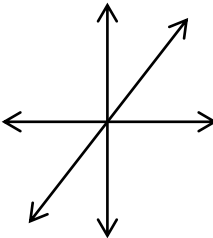


Activity 2: Electron Configuration

4s _____ Find the electron configuration for Na and Al³⁺	
3p _____	4s _____
3s _____	3p _____
2p _____	3s _____
2s _____	2p _____
1s _____	2s _____
	1s _____

Write the orbital notations for Li (# e:3) and Fe (# e:26)

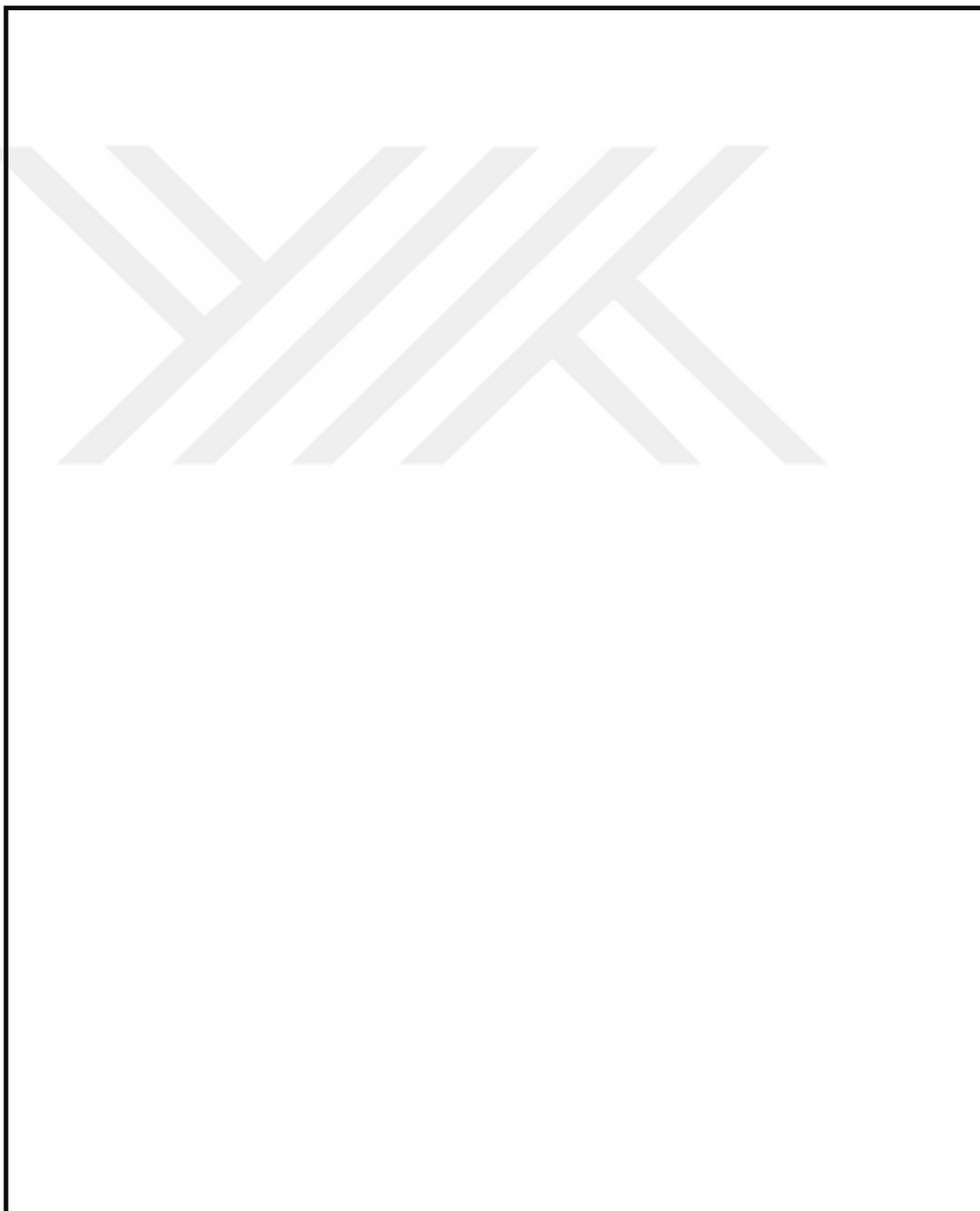
Activity 3: Orbital Shapes

				
S-orbital	p_x -orbital	p_y -orbital	p_z -orbital	All three p orbitals together

Applications

❖ *Readings: Please read Applications parts on page 36-39*

Pre Activity Task: Write a short summary about Atomic clocks and the definition of the second, Fluorescent Lights, Sodium lamps and Lasers based on what you read and what you know. Please be explicit as much as possible. Please also give examples for electron configurations.



Activity 1: Laser Simulation

1. Open the simulation by downloading it from the following link:
<https://phet.colorado.edu/en/simulation/lasers>
2. Click on the “One Atom (Absorption and Emission)” tab.
3. Here, you will try to obtain lasing by changing some variables such as light intensity, mirror reflectivity, energy level distance and lifetime. What are the optimum conditions for lasing? Write down the variables you found for optimum lasing.



Activity 2: Neon Lights & Other Discharge Lamps

1. Open the simulation by downloading it from the following link:
<https://phet.colorado.edu/en/simulation/discharge-lamps>
2. Click on the “One Atom” tab.
3. You will make observations by changing the conditions on voltage and the type of atoms.

